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Comparison of Commercial Electromagnetic Interference Test Techniques to NASA Electromagnetic Interference Test Techniques

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Prepared for Marshall Space Flight Center
under Contract H–30231D
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LIST OF ACRONYMS

ac	alternating current
C	capacitance
CE	European Community (Communaute European)
COTS	commercial off the shelf
dc	direct current
DO	document
EC	European Community
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EN	European Standards (Normes Européennes)
EUT	equipment under test
FCC	Federal Communications Commission
G	ground conductance
IEC	International Electro-Technical Commission
L	inductance
LISN	line impedance stabilization network
R	resistance
RF	radio frequency
RTCA	Radio Technical Commission for Aeronautics
TF	transfer function

NOMENCLATURE

c	commercial results
K_i	constant
K_n	transfer function constant
K_v	constant
n	NASA results
Q	quality factor
$\mathrm{V_n}$	noise voltage
V_s	source voltage
$\mathrm{Z_L}$	load impedance
$\mathrm{Z_s}$	source impedance

CONTRACTOR REPORT

COMPARISON OF COMMERCIAL ELECTROMAGNETIC INTERFERENCE TEST TECHNIQUES TO NASA ELECTROMAGNETIC INTERFERENCE TEST TECHNIQUES

1. PURPOSE OF THE STUDY

NASA Specification SSP30237A, "Space Station Electromagnetic Emission and Susceptibility Requirements for the Electromagnetic Compatibility," establish the Space Station electromagnetic emission and susceptibility requirements as well as design requirements for the control of electromagnetic emission and susceptibility characteristics of electronic, electrical, and electromagnetic equipment and subsystems designed or procured for use by NASA. The applicability of the emission and susceptibility requirements completely depends on the intended location or installation of the equipment or subsystem within the Space Station. SSP30237A denotes the equipment or subsystem as internal and external equipment as the intended location site. Internal equipment applies to equipment located inside a module or node. External equipment applies to all equipment located external to modules and nodes. SSP30237A relies on MIL–STD–461 as its framework document since it has been tailored based upon previous work on a known electromagnetic environment for the Space Station. The MIL–STD–461 limit was adjusted based on power requirements and receiver sensitivity as well as margin for safety and the desire to limit system-level compatibility concerns. The detailed test procedures for SSP30237A are contained in SSP30238A, "Space Station Electromagnetic Techniques."

The work documented in this report was initiated to develop analytical techniques required to interpret and compare space system electromagnetic interference (EMI) test data with commercial test data using NASA Specification SSP30237A. Such information is required to accommodate the use of commercial off-the-shelf (COTS) equipment in space vehicles. Interest in using commercial electromagnetic compatibility (EMC) requirements in space equipment comes primarily from the EMC directive issued within the European Union and enforced as of January 1, 1996. The EMC directive requires commercial manufacturers to design and test their equipment to EMI test standards similar to those required for aircraft, military, and space equipment.

NASA has performed tests per SSP30237A and has a database of subsystems EMI test data. The system designers use this database for locating and colocating various subsystems within the space vehicle. If the SSP30237A data cannot be correlated with the data obtained from the corresponding commercial test requirements, then the equipment may either be placed in an environment where it can be susceptible or can cause susceptibility without violating the system-level performance requirements. In addition, if correlation is not possible, the system designer may decide to remove a subsystem from a questionable to a benign environment. This may cause an extensive redesign and impact on cost and schedule of the entire system.

2. SCOPE OF WORK

The detailed test procedures for SSP30237A are contained in SSP30238A. The following are the major EMI test requirements used extensively by the commercial market:

- Code of Federal Regulations – Part 15 (Federal Communications Commission (FCC) Part 15), which addresses conducted and radiated emission in the frequency range of 450 kHz to 1 GHz. The FCC divides the EMC environment into class A and class B requirements for office and household environment, respectively.

- EMC Directive 89/336/EEC for use in the European Community (EC), which specifies both emission and susceptibility (immunity) requirements. The EC (designated CE (Communaute European)) documents divide the EMC environment into household and light industrial environment in one class and industrial environment into another class. The EMC requirements rely on a series of test methods developed by the International Electro-Technical Commission (IEC) and are designated either as IEC–1000–X–X, or as EN (European Standards) 550XX Emission and Immunity requirements.

- RTCA (Radio Technical Commission for Aeronautics)/DO (Document)–160C standard is used in avionics industry for use in commercial airlines. The original version of the document was tailored from MIL–STD–461, but has been updated over the years and contains requirements beyond the MIL–STD–461 test methods, such as lightning and environment tests. Since Space Station requires equipment similar to that used in commercial airlines, this standard will be important when purchasing navigational and communication equipment.

The main objective of this study is to correlate the commercial requirements to SSP30237A requirements and to develop transfer functions (TF's) between the various standards to translate one into another.

There are areas where the commercial requirements do not fully cover the requirements specified in SSP30237A. For example, when comparing CE01 to IEC–1000–3–2, the commercial standard does not fully cover the frequency range. CE01 requires the measurement of conducted emissions from 30 Hz through 15 kHz, whereas IEC–1000–3–2 only requires the measurement of the harmonic current emission up to the 40th harmonic. Therefore, comparison between IEC–1000–3–2-certified equipment and SSP30237A-qualified equipment will only be applicable if the interharmonic emissions are not of concern and if the equipment does not have local oscillators <10 kHz such as in direct current (dc)-to-alternating current (ac) switching mode power supplies. SSP30237A requires CE01 testing for dc power leads only, whereas IEC–1000–3–2 is not applicable to dc systems. Since NASA plans on procuring COTS equipment designed for 115 or 220 V, 50- or 60-Hz operation, we plan to analyze ac equipment against the CE requirements of SSP30237A to provide a reference point for NASA engineers.

The scope of work included identifies differences between various measurement instruments as well as components used in test setups, such as line impedance stabilization networks (LISN's) and feed-through capacitors. Measurement instruments are generally similar in related specifications; however, there are some differences that require careful examination. For example, the LISN's called out in the NASA specifications are different from the LISN's in the DO–160C specifications and the LISN's specified in the majority of IEC–1000–4–X requirements are still of different design.

Our plan of study included not only comparing the test results from various test setups in the laboratory, but also verifying the results using Cadence Design Systmes, Inc. PSpice® circuit simulation software of the actual setup used in the laboratory. Only when these two data matched did we develop a high degree of confidence in using the final conclusions derived from the study.

The scope of the study also included the following:

- Develop models using PSpice simulation techniques for various EMI test standards. Then compute the response of the setup over the entire frequency range covered by the standard under consideration.

- Include the cable parameters, such as length of the cable, height above the ground plane, whether the cable runs behind, in front, or alongside the equipment under test, and other configuration issues. These all can be addressed by including the cable capacitance (C), inductance (L), resistance (R), and ground conductance (G) for the type and length of the cable used in the actual laboratory setup. These parameters come from standard high-frequency transmission line theory that covers the entire frequency range from low to high frequencies. The parameters can be lumped for short cables or can be distributed, if necessary, for better accuracy.

- Develop two different response signals at the equipment under test (EUT) in two different EMI test standards simulated on PSpice (one NASA and another commercial). Then generate the TF to correlate the two. For example,

  $TF_{nc}(\omega)$ = Transfer function that gives the NASA results (n) from a commercial result (c).

- Summarize the results of the study to guide the NASA engineer in applying commercial EMI requirements in space vehicles.

Identify various assumptions or idealized boundary conditions that were used to obtain the results and EMI limit comparisons after performing the work described above. This will alert NASA engineers to possible pitfalls in applying the results in a critical area and indicate that additional testing may be necessary on commercially procured equipment.

3. TECHNICAL APPROACH

The basic approach was to analyze corresponding test methods and limits from SSP30237A and the applicable requirements in the FCC regulations, the EC EMC requirements, and/or RTCA/DO–160C. We then developed fitting TF's based on the comparison of the two data sets for translating one of the commercial data sets into the NASA SSP30237A electromagnetic environment envelope.

Table 1 lists the SSP30237A test applicability by equipment class. We first concentrated on the NASA CE01 and CE03 requirements, and the corresponding commercial requirements as listed in table 2, which shows how each of the SSP30237A requirements are analyzed against the various commercial standards. The analysis was performed by evaluating various instrumentation, measurement techniques, and applicable limits for each of the test methods. This included evaluations of different LISN's, feed-through capacitors, spectrum analyzers, oscilloscopes, and other test instrumentation that are used in different test methods which could lead to differences between measured quantities. For example, CE01 and CE03 require the use of a 10-µF capacitor on all power lines and measuring the radio frequency (RF) current directly on the power line using an RF current probe and EMI receiver. FCC Part 15 and EN55022 each require an LISN on the power line under test and the measurement of a voltage across a resistor in the LISN. Therefore, the two limits are in different units and cannot be simply compared. This requires an analysis to determine the relationship between the measured quantities and thereafter developing the TF between the two.

Table 1. SSP30237A test applicability by equipment class.

	Class			
Test	**IA**	**IB**	**IC**	**Description**
CE01	X	X	X	Conducted emissions, narrowband, dc power leads, 30 Hz–15 kHz
CE03	X	X	X	Conducted emissions, narrowband, dc power leads, 15 Hz–50 MHz
CE06	X	X		Conducted emissions, narrowband and broadband, antenna terminals, 15 kHz–50 GHz
CE07	X	X	X	Conducted emissions, spikes, dc power leads, time domain
CS01	X	X	X	Conducted susceptibility, narrowband, dc power leads, 30 Hz–50 kHz
CS02	X	X	X	Conducted susceptibility, narrowband, dc power leads, 50 kHz–50 MHz
CS03	X			Conducted susceptibility, narrowband, intermodulation, two signal, 15 kHz–20 GHz
CS04	X			Conducted susceptibility, narrowband, rejection of undesired signal, 15 kHz–20 GHz
CS05	X			Conducted susceptibility, narrowband, cross modulation, 15 kHz–20 GHz
CS06	X	X	X	Conducted susceptibility, spikes, dc power leads, time domain
CS07	X			Conducted susceptibility, narrowband and broadband, squelch circuits
RE01	X	X	X	Radiated emissions, narrowband, magnetic field, 30 Hz–250 kHz
RE02	X	X	X	Radiated emissions, narrowband and broadband, electric field, 14 kHz–20 GHz
RE03	X	X		Radiated emissions, spurious and harmonics
RS02	X	X	X	Radiated susceptibility, spikes, induction, time domain
RS03	X	X	X	Radiated susceptibility, electric field, 14 kHz–50 GHz
LE01	X	X	X	Leakage current, ac power user, power frequency

Table 2. NASA versus commercial EMI requirements.

SSP 30237A Requirement	FCC Requirement	EC Requirement	DO–160C Requirement
CE01	–	IEC–1000–3–2	–
CE03	Part 15	EN 55022	Section 21
CS01	–	IEC–1000–4–13	Section 18
CS02	–	IEC–1000–4–6	Sections 18 and 20
CS06	–	IEC–1000–4–5	Section 17
RE01	–	–	Section 15
RE02	Part 15	EN 55022	Section 21
RS02	–	IEC–1000–4–8	Section 19
RS03	–	IEC–1000–4–3	Section 20

Notes:

- Test methods CE06, CS03, CS04, CS05, CS07, and RE03 are not EMI tests per se, but are quality assurance specifications of receivers best left to the manufacturer and procurement requirements.

- There are no equivalent commercial specifications for CE07, which measures switching transients.

- RE01 is not addressed.

4. PSPICE COMPUTER SIMULATIONS

The PSpice circuit simulation of the following four setups are shown in figure 1:

1. NASA SSP30238A, Revision C
2. DO–160C, Section 21
3. FCC Part 15, 150 kHz to 30 MHz
4. MIL–STD–462D (similar to IEC and EC CE01 standards).

These simulations include applicable LISN's. The details of the complete simulation circuit models are given in appendix A.

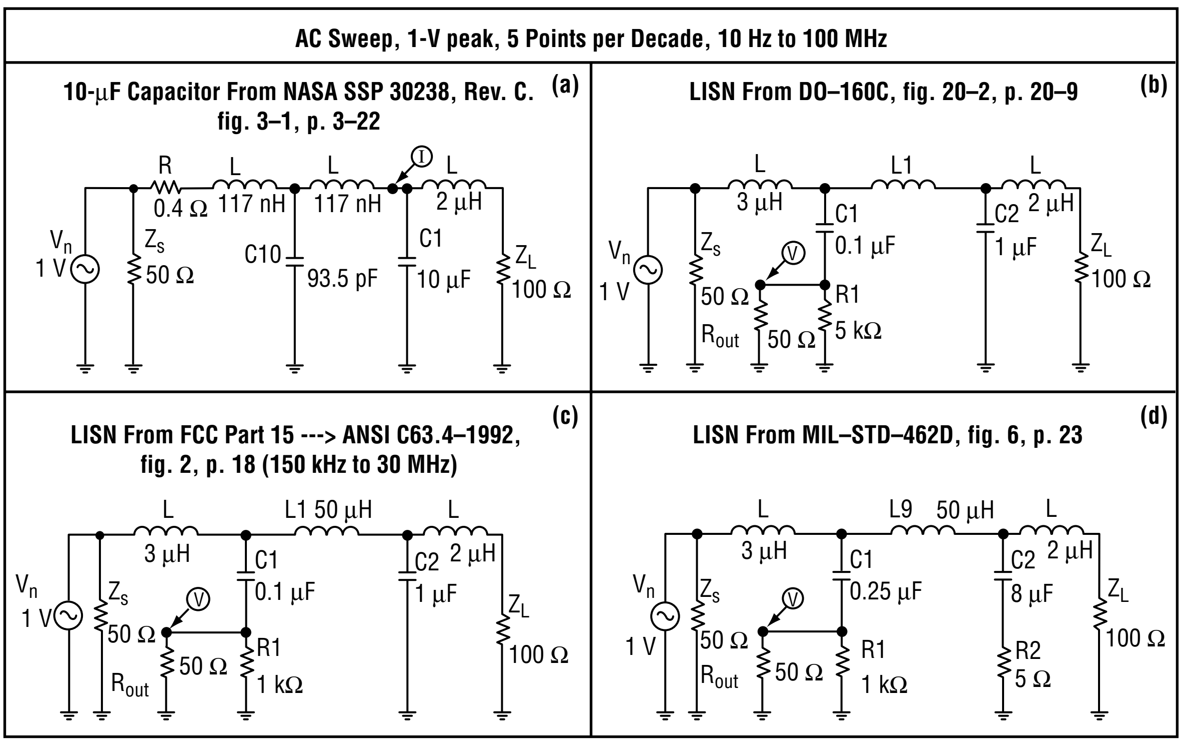


Figure 1. The four PSpice simulation models, including the cable inductance and capacitance in a T network.

5. LABORATORY SETUPS

One of the major concerns in comparing different EMI test requirements is the test setup. For instance, the majority of the IEC–1000–4–X requirements specify that the equipment under test be placed on an insulated surface ≈80 cm from the ground plane, whereas SSP30237A requires that the unit be placed ≈5 cm above the ground plane. This would cause major differences in test results that must be carefully investigated. For the purpose of conducted emission testing, the cable was modeled as a transmission line having C, L, R, and G parameters in an equivalent T network as shown by 117 nH, 117 nH, and 93.5 pF in circuit model a in figure 1. The cable having the following parameters was used in the actual laboratory setup:

Length:	1 m
Type:	coaxial RG–3/U
Characteristic impedance:	50 Ω

Calculated values of the transmission line parameters of the cable:

$C = 93.5$ pF/m
$L = 234$ nH/m
$R = 0.40$ Ω/m
$G =$ negligible.

6. MEASUREMENT TECHNIQUES

The standards being considered use very similar measurement techniques. These standards use measurement receivers to measure voltages and current probes to measure currents. These standards also use current probes to measure current drops across a known resistor to determine a voltage with respect to a given frequency range. Conversion factors are then applied based upon calibration of the equipment used to perform the measurement and then a comparison is made to a given emission limit. However, each method has various differences in the approach for maintaining consistency within the testing. The IEC–1000–4–X series of documents recommend the use of coupling/decoupling networks to match the typical installation impedance of various cables to the test cable configuration. The idea is to minimize the distortion between the laboratory measurement and a typical field measurement. SSP30238A relies on proper equipment calibration to perform the measurements. The values obtained from the various test specifications required adjustments to compare limits and test results. These adjustments were handled on a test method basis.

As for the frequency range, the test requirements were reviewed to determine if they overlap the entire specifications. If not, the differences were taken into account as needed.

The measurement process for each setup involved the collection of 33 data points. Depending on the setup, either dBμA (decibelmicroamperes) or dBμV (decibelmicrovolts) was measured as a function of frequency. The selected frequencies corresponded to the frequencies that were provided as a result of the PSpice analysis. The frequencies covered the ranges as identified in NASA CE01 (30 Hz to 15 kHz) and CE03 (15 kHz to 50 MHz). The first data point was taken at 25 Hz and the last data point was taken at 63.1 MHz, thus completely covering the required ranges. During this scan, the spectrum analyzer bandwidth was changed depending on the frequency range under investigation. The bandwidths used corresponded to those identified in MIL–STD–462D, p. 13, Table II, “Bandwidth and Measurement Time.”

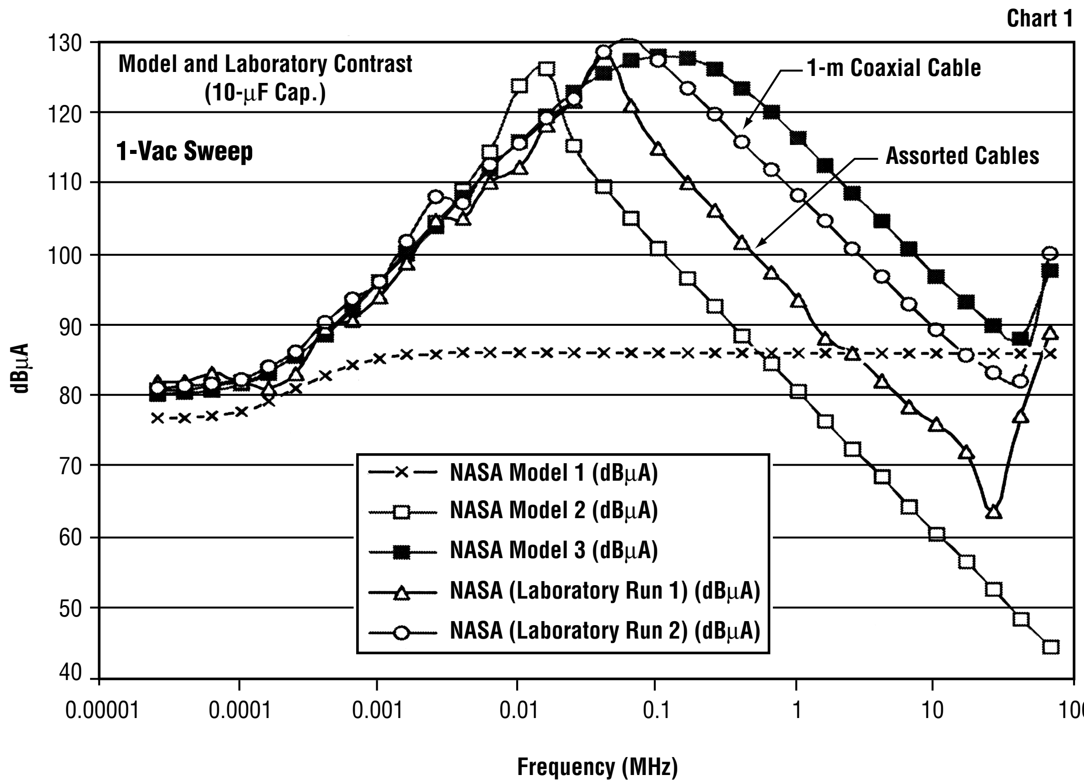
Preceding each data point measurement, the amplitude of the 1-Vac signal had to be verified and maintained. The 1-Vac signal corresponded to 120 dBμV on the spectrum analyzer. It was quickly determined that adjustments to the frequency generator or RF amplifier had to be made for virtually every frequency to maintain the 120 dBμV necessary for this study. Once the correct amplitude had been established, the current measurement in dBμA for CE01 and CE03 or the voltage measurement (in dBμV for the LISN’s) could be made.

The current measurements for NASA CE01 and CE03 required two current probes to cover the entire frequency range. Each current probe has a calibration curve plotting its “current probe factor” as a function of frequency. The data gathered by these probes have been adjusted to include the probe’s factor.

Appendix A identifies where the probes were placed. Appendix B contains the graphs of the collected data. Appendix C identifies the test equipment used.

7. LABORATORY TEST RESULTS

The simulations and the laboratory results on the four test setups are fully documented in appendix B and summarized in the next section. It is noteworthy that the type of cable and its configuration and layout used in the actual setup made a significant difference in the results. Figure 2 shows conducted emission in the NASA SSP30237A setup with randomly laid cables and with a 1-m coaxial cable. The response measured in the laboratory with the coaxial cable shifts significantly to the right. This shift is also seen by the simulation results, which included the C, L, and R parameters of the cable.



NASA Model 1 (dBμA):	The first of three PSpice models involving the 10-μF capacitor.
NASA Model 2 (dBμA):	The second of three PSpice models involving the 10-μF capacitor, this time with Z_s (50 Ω) in parallel to the EUT and inductance values provided for the leads.
NASA Model 3 (dBμA):	The third of three PSpice models. Much like model 2 but taking in account transmission line characteristics.
NASA (Laboratory Run 1) (dBμA):	Laboratory data involving the 10-μF capacitor. Connection between the EUT and the capacitor contains assorted banana leads.
NASA (Laboratory Run 2) (dBμA):	Laboratory data involving the 10-μF capacitor. Connection between the EUT and the capacitor contains 1-m coaxial cable.

Figure 2. Decibel measurements on NASA test setups with various models.

A parametric study made with PSpice simulation shows sensitivity of the results to one more parameter, the cable resistance, in determining the peak of the response. The current measurement, in amperes, was taken on the lead between the EUT and the capacitor with three different values of the cable resistance, namely 0.01, 0.2, and 0.4 Ω . For these cable resistance values in the NASA model, the response peaks are shown in figure 3. The response with a low resistance of 0.01 Ω has a very high and sharp peak, whereas the 0.4 Ω resistance significantly damps out the response to a low peak. This was expected, as low resistance results in a high-Q (quality factor) circuit having a high and sharp peak at the resonance frequency, 100 kHz in this case.

Figures 2 and 3 illustrate how seemingly minor test setup variations, such as the cable type and gauge, can affect the overall EMC data. This indicates that for properly comparing similar specifications, a careful and robust analysis of the similarities and differences in the setups is required.

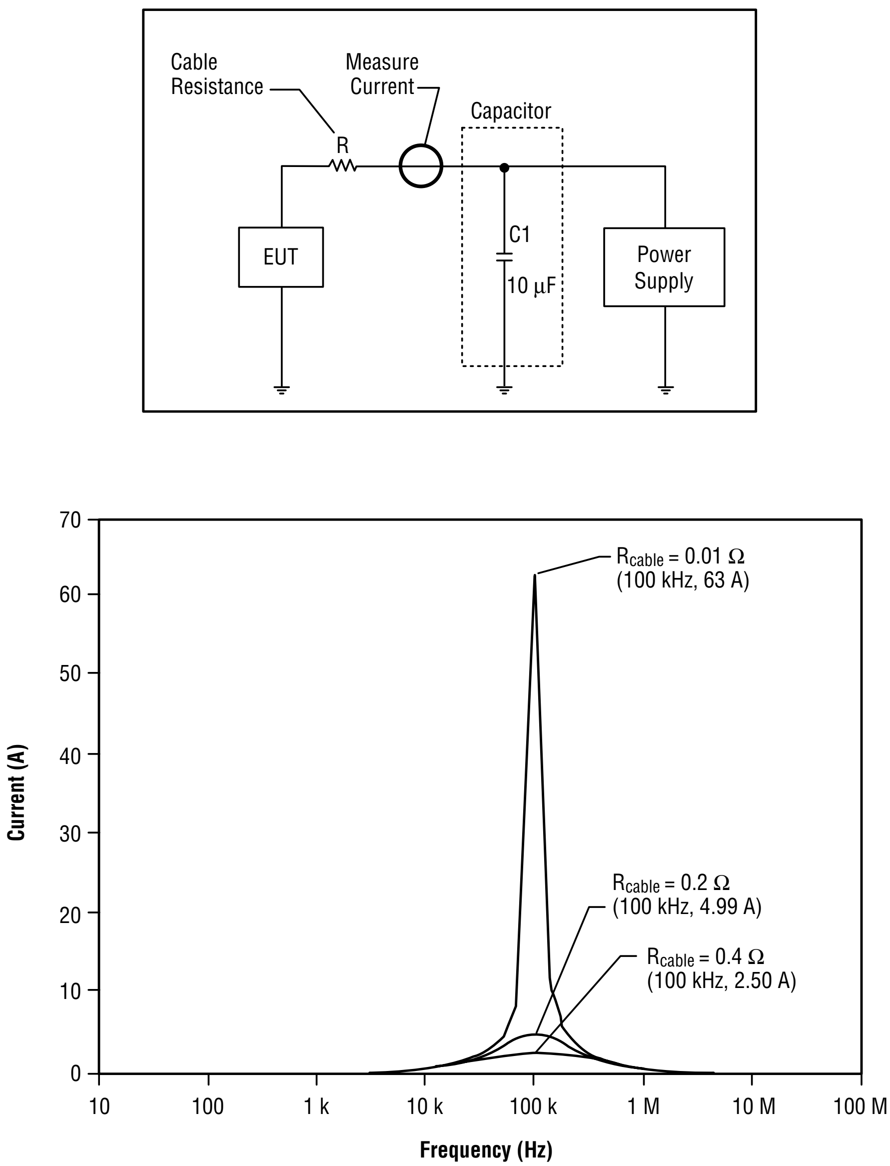


Figure 3. Effect of cable resistance on the peak response at the resonance frequency.

8. COMPARISON OF SIMULATION WITH TEST RESULTS

The computed results from the PSpice simulation and the laboratory test results for the standards considered in the study compare well after accounting for the cable parameters. Figure 4 summarizes the comparison with four setups for the conducted emission tests.

Appendix B provides full details of these results.

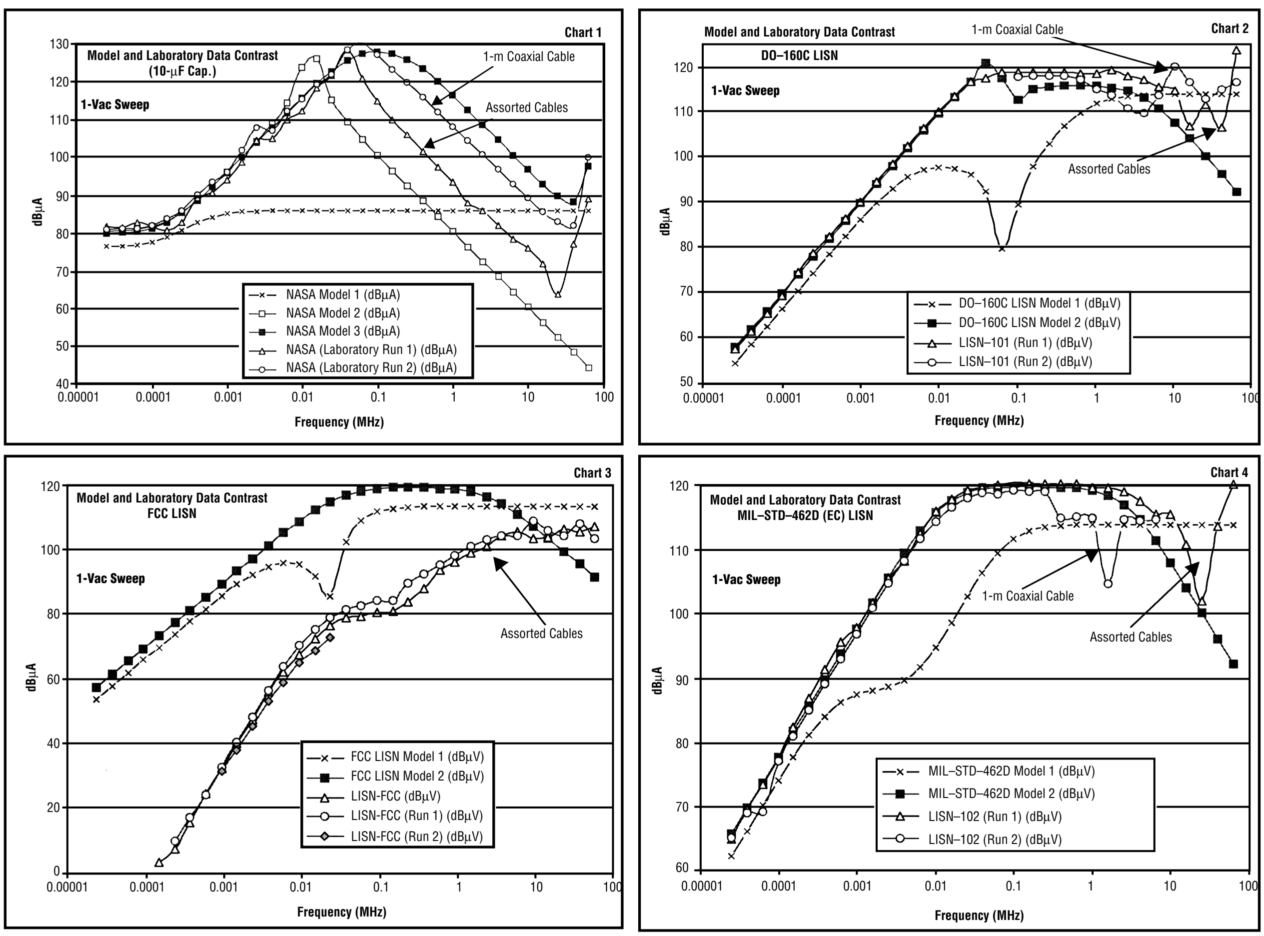


Figure 4. The PSpice simulation results and the laboratory measurements compare well for the four EMI test setups.

9. RELATIONSHIP BETWEEN ONE TEST TO ANOTHER

The relation between one test to another can be seen as a TF. Since the difference between any two responses will be, in general, a function of frequency, the TF relating the two would also be a function of frequency. For example, the TF may be in the following form:

$TF_{nc}(\omega)$ = Transfer Function as a function of frequency that gives the NASA results (n) from a commercial result (c) at a given frequency.

Once the comparison between the NASA and the commercial tests have been performed as described in the previous section, various results can now be related and correlated using the TF defined above. However, we first wish to develop a correlation process that will be applicable to the present study. One difficulty in correlating different results is that they may be in different units, such as one in dBμV and another in dBμA. This must be considered and accounted for in developing the TF.

In selecting a suitable form of the TF, we considered the following:

- Since the response we plot in the EMI standard is always expressed in decibels, we decided to also formulate the TF in decibels.

- The correlation can be developed using an equivalent two-port circuit box representing the TF that converts one of the commercial test results into the NASA results. The concept is shown in figure 5.

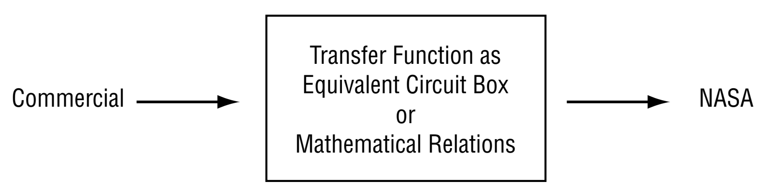


Figure 5. Commercial to NASA conversion of test results.

From the correlation study, the equivalent circuit parameters of the TF box can be determined. However, this process would be extremely difficult. Moreover, it would not have any additional value as opposed to finding the TF solely by using a mathematical relation for converting one result into another. We chose the mathematical approach and the least-square method of finding the best mathematical fit in a polynomial form for developing various TF's. Readily available statistical software packages in Microsoft® Excel spreadsheets or in advanced tools such as Wolfram Research's Mathematica® can be used for this purpose.

Once the issue of fitting the TF was settled, we then evaluated the following options in formulating a suitable mathematical form of the TF:

$$dB_1 = f\,(dB_2) \quad , \tag{1}$$

that is, write dB_1 as a function of dB_2. This approach led to difficulties in correlating limit 1 with limit 2, because many decibels are double-valued functions, making such functional relation between the two difficult to establish:

$$dB_1 = TF(\omega)*dB_2 \quad . \tag{2}$$

This approach also led to difficulty when dB_1 and dB_2 crossed the zero gain line, resulting in singularities where correlation by the least-square polynomial fit became extremely difficult:

$$dB_1 = dB_2 + TF_{12} \quad . \tag{3}$$

This form has multiple advantages:

- It eliminates the singularity and the double-value difficulties.
- It also eliminates the effect of different driving voltage magnitudes in the setups.
- Additionally, it can take into account different units of dB_1 and dB_2.

For example, if one response is measured in voltage and the other in current, then the measured response can be written as a constant multiple of the driving source voltage V_s as:

$$\mu V = K_v\, V_s \quad , \tag{4}$$

for setup 1, and

$$\mu I = K_i\, V_s \quad , \tag{5}$$

for setup 2, where K_v and K_i are constants having their own units (not necessarily the same).

Then,

$$dB\mu V = 20 \log K_v + 20 \log V_s \tag{6}$$

and

$$dB\mu I = 20 \log K_i + 20 \log V_s \quad . \tag{7}$$

Taking the difference of the two, we get

$$dB\mu I - dB\mu V = 20 \log K_i - 20 \log K_v = TF_{12}(\omega) \quad . \tag{8}$$

This can then be written in the desired form:

$$dB_1 = dB_2 + TF_{12}(\omega) \quad . \tag{9}$$

Thus, the TF formulated this way can accommodate any two dB's in two different units by the TF having its own unit that links different units in the two different setups. It also makes the results independent of the source voltage magnitude.

10. DEVELOPING TRANSFER FUNCTIONS BY POLYNOMIAL FIT

If we develop the TF such that

$$TF_{nc}(\omega) = \text{NASA limit} - \text{commerical limit} \ , \tag{10}$$

then, from a given commercial limit, the NASA limit can be obtained simply by adding into the commercial limit the TF_{nc}. That is,

$$\text{NASA limit} = \text{Commercial limit} + TF_{nc}(\omega) \, . \tag{11}$$

The primary purpose of this study has been to develop TF's for determining the NASA limit from various commercial limits used in COTS.

Having formulated the TF as described above, the TF is developed as an nth-order polynomial function of frequency that best fits the data such that the variance between the predicted values and the actual values is the least.

The TF's in the form described above were developed using two alternative mathematical tools, namely the widely used Excel spreadsheet and the more advanced Mathematica. We found that Mathematica gave a better fit because of its better algorithm and built-in criteria of terminating the iterative process of fitting a polynomial. Figure 6 is an example of the results using Mathematica for finding one such TF. The solid line is the polynomial fit and the dots are the actual data points that were input. The vertical axis is the TF decibels and the horizontal axis is (log *f*). The comparison of the two shows a good fit.

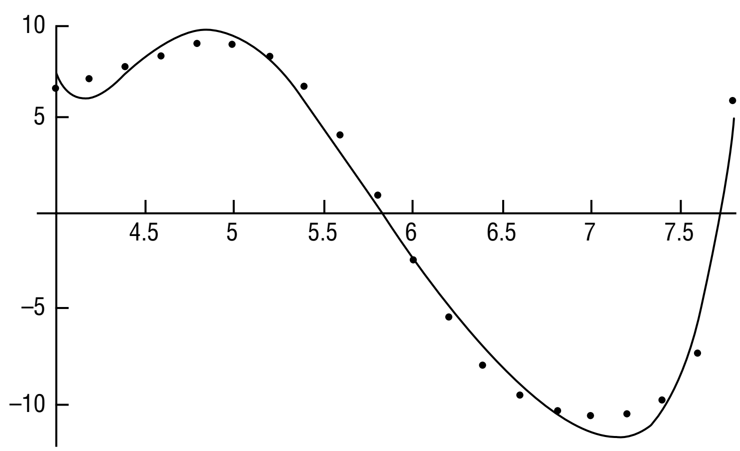


Figure 6. Least-square polynomial fit (solid line) for given data points (dots) using Mathematica.

The Mathematica code and the run for all cases are given in appendix D. The results, however, are summarized in table 3, which lists the coefficients of the best-fit polynomials of the order six. The polynomials of the order 3, 4, 5, 6, and 7 all gave reasonably good correlation. However, we chose to summarize the results of the sixth-order polynomial fits for better accuracy.

Use table 3 to obtain the NASA limit by adding the following TF into the commercial limit:

$$\mathrm{TF} = K_0 + K_1 (\log f) + K_2 (\log f)^2 + \ldots + K_6 (\log f)^6 \ , \tag{12}$$

where the coefficients of the TF constants (K_n) are as given in table 3.

Table 3. Summary of the sixth-order polynomial coefficients for the best fit TF.

TF Coefficients	To NASA CE01 From EC–1000–3–2	To NASA CE03 From FCC Part 15	To NASA CE03 From EN 55022	To NASA CE03 From DO–160C, Sec. 21
K_0	–162.923	27304.3	30722.0	42469.7
K_1	482.231	–29226.0	–33003.7	–44626.9
K_2	–483.911	12879.3	14574.2	19304.5
K_3	233.379	–2992.82	–3389.87	–4404.29
K_4	–59.2512	387.263	438.661	559.717
K_5	7.62227	–26.4969	–29.9915	–37.6239
K_6	–0.389729	0.749952	0.847632	1.04651

11. CONCLUSIONS

This report documents the results of the development of analytical techniques required to interpret and compare space system EMI test data with commercial test data using NASA Specification SSP30237A, “Space Station Electromagnetic Emissions and Susceptibility Requirements for Electromagnetic Compatibility.” This information is required to accommodate the use of COTS equipment in space vehicles. For each of the test methods compared, we analyzed the differences in the test setups, instrumentation used, measurement techniques, frequency range, relationship between measured quantities, difference in the limits, and the applicability of the requirements. Once the analysis had been performed, a process was developed to relate the SSP30237A test data with the corresponding commercial requirements.

Using the mathematical form of the TF defined in this report, four TF’s for obtaining the NASA limits from one of the commercial limits were developed. The least-square polynomial fit algorithm of Mathematica was employed for this purpose. The coefficients of such TF’s are summarized in table 3.

The variations in the laboratory test setup, in particular, the cable length; layout; types, i.e., coaxial, twisted, or randomly laid out; and resistance, make a significant difference in any two tests.

Since the cable length, layout, and type are equipment specific, it is concluded that using the TF’s developed by the technique described in this report is not practical to use and could be misleading.

APPENDIX A—DESCRIPTION OF VARIOUS PSPICE MODELS SIMULATING THE EMI TEST SETUPS

Figure 7 shows the two general configurations under study. At left is the implementation of the 10-μF capacitor as cited in NASA's CE01 and CE03. At right is an LISN as employed in DO–160C, which is similar in setup to other EMI test techniques.

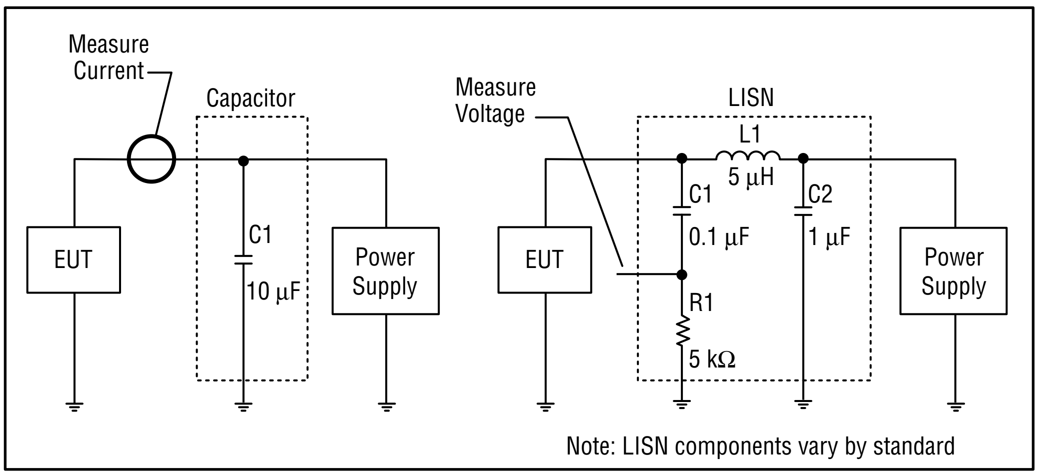


Figure 7. PSpice simulation general schematic for CE01, CE03, and LISN models.

Four schematics or configurations have been developed to simulate the LISN's and the 10-μF capacitor as required for this study. These schematics are included in figures 8–13.

For this study, the EUT was represented as a 1-V noise source with an impedance of 50 Ω. For simplification purposes, the power supply was replaced by a 100-Ω load. The illustrations below indicate how the EUT (noise source) and power supply (100-Ω load) were employed into the circuits from the previous figure.

Figure 8, model 1 is preliminary to compare with laboratory data. After obtaining some laboratory data, model 2 was developed which had a stronger correlation.

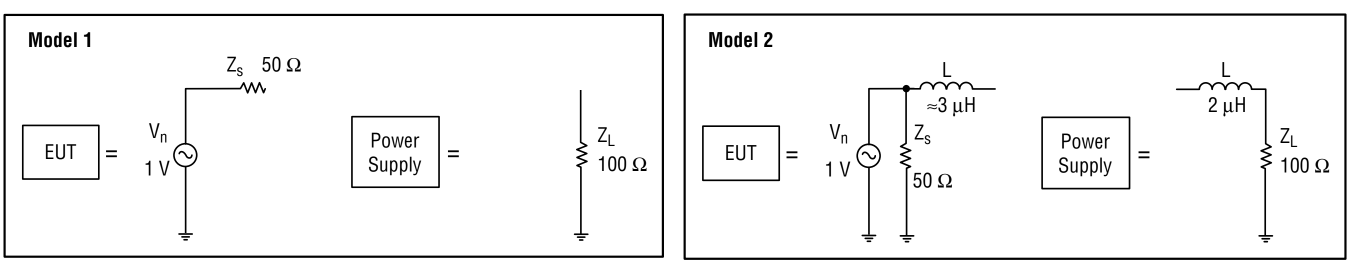


Figure 8. PSpice simulation EUT and power supply as implemented in the models.

For CE01 and CE03 (which uses the 10-μF capacitor), a current probe is used to measure the noise emitted by the EUT, typically measured in dBμA. Working with the LISN's, voltage measurements in dBμV are made instead of dBμA. To compare these measurements, a frequency generator was used to provide a signal. A 1-V sinusoidal signal was selected to represent the "noise" emitted by the EUT. Thus, the frequency generator used to provide the signal represented the EUT. For the PSpice models, the frequency was sweep from 10 Hz to 100 MHz at five points per decade. This would cover the entire frequency range as required for CE01 and CE03. To facilitate the comparisons as required by this study, the laboratory data were collected at the same set of frequencies as those generated by PSpice.

Figure 9 shows model 3 for the 10-μF capacitor as used by NASA. This model was the third attempt to model the results as obtained in the laboratory. The 0.4-Ω resistor, 117-nH inductors, and the 93.5-pF capacitor take into account transmission line characteristics.

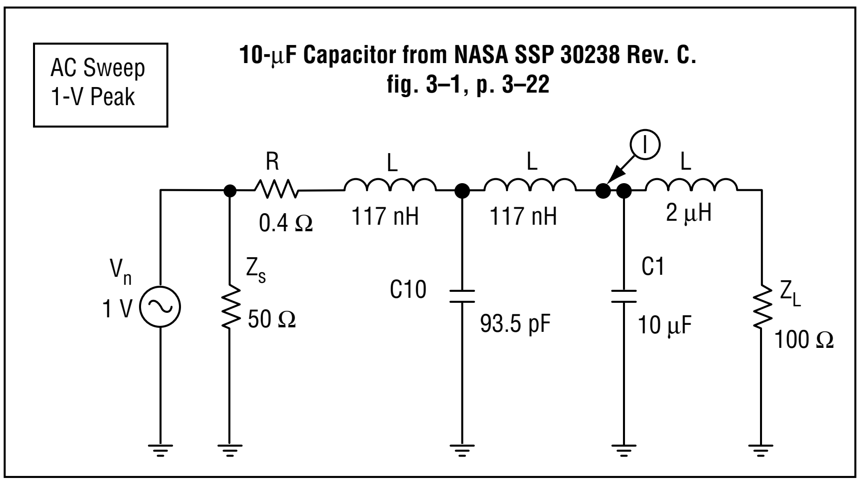


Figure 9. PSpice simulation EUT and power supply as implemented in the models.

Figure 10 shows model 2 for the 5-mH LISN as used in DO–160C. This model was the second attempt to model the results as obtained in the laboratory.

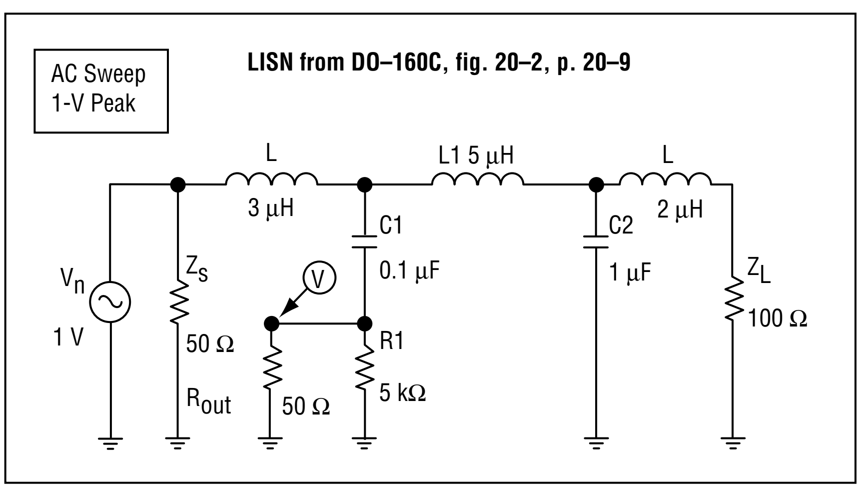


Figure 10. DO–160C LISN setup schematic for PSpice.

Figure 11 shows model 2 for the 50-µH LISN as used in FCC Part 15. This model was the second attempt to model the results as obtained in the laboratory.

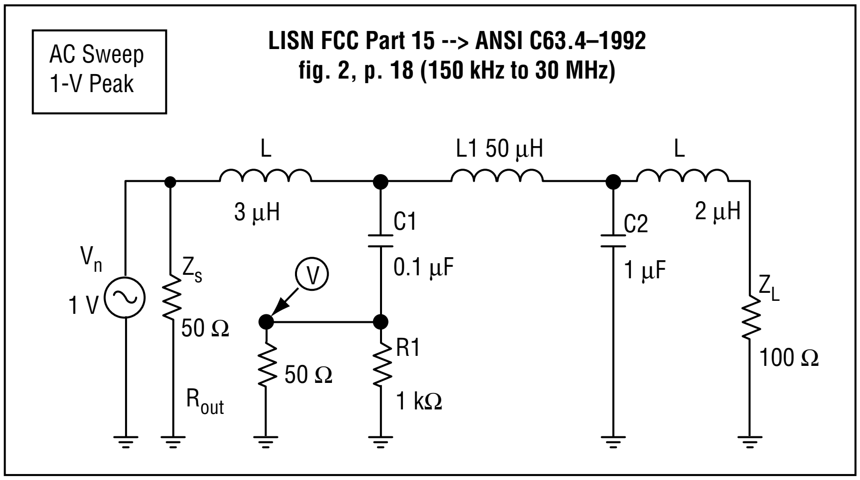


Figure 11. FCC LISN setup schematic for PSpice simulation.

Figure 12 shows model 2 for the 50-µH LISN as used in MIL–STD–462D as well as in EC testing. This model was the second attempt to model the results as obtained in the laboratory.

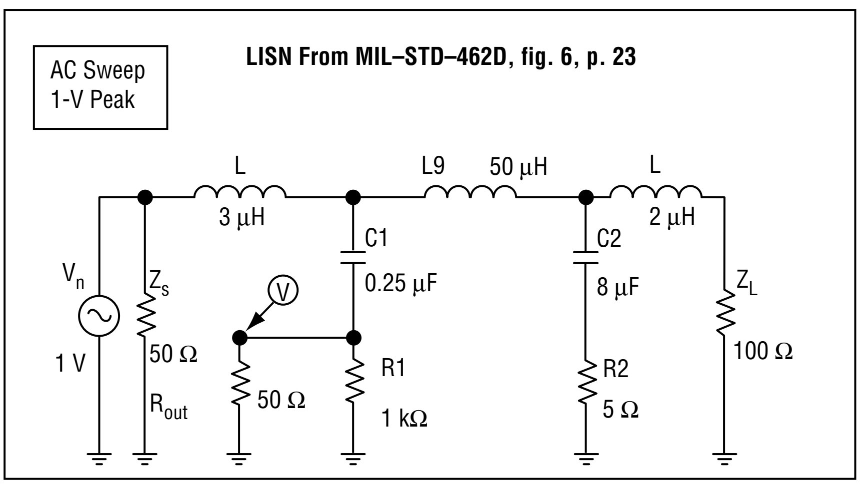


Figure 12. EC LISN setup schematic for PSpice simulation.

Figure 13 shows the initial models of figures 9–12 without the lead inductance values.

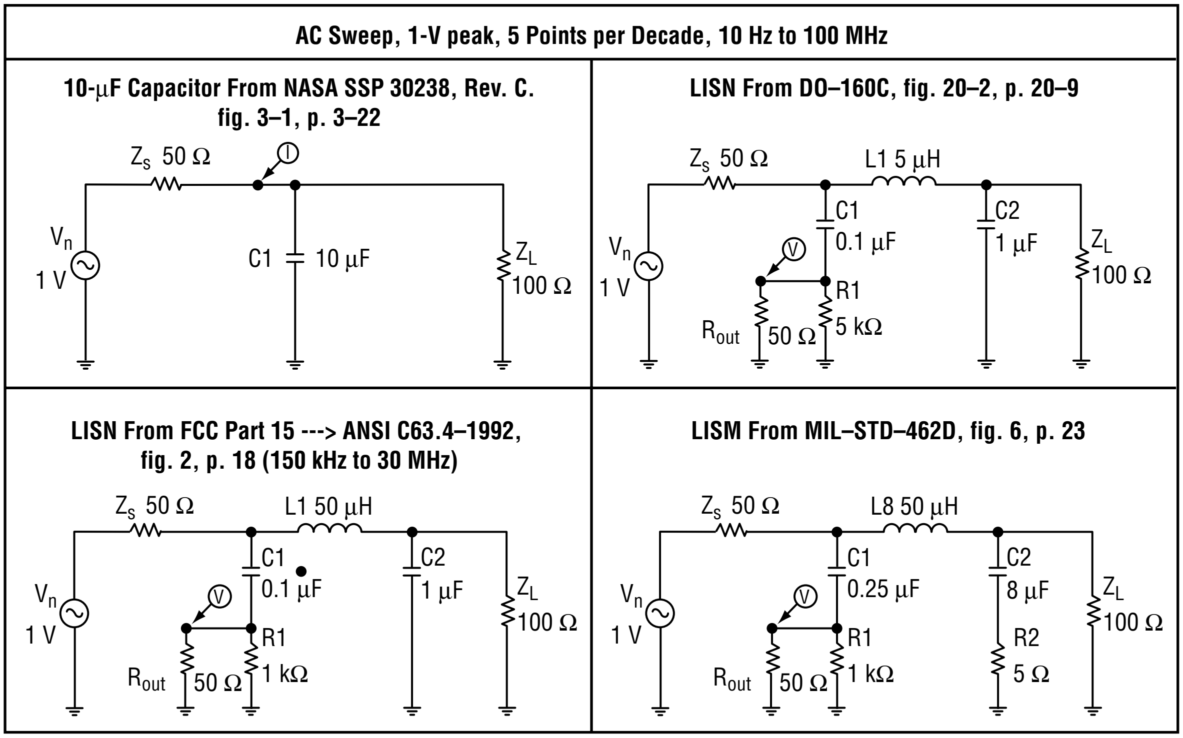


Figure 13. The four initial PSpice simulation models.

APPENDIX B—DETAILED SIMULATION AND LABORATORY RESULTS AND THEIR COMPARISON

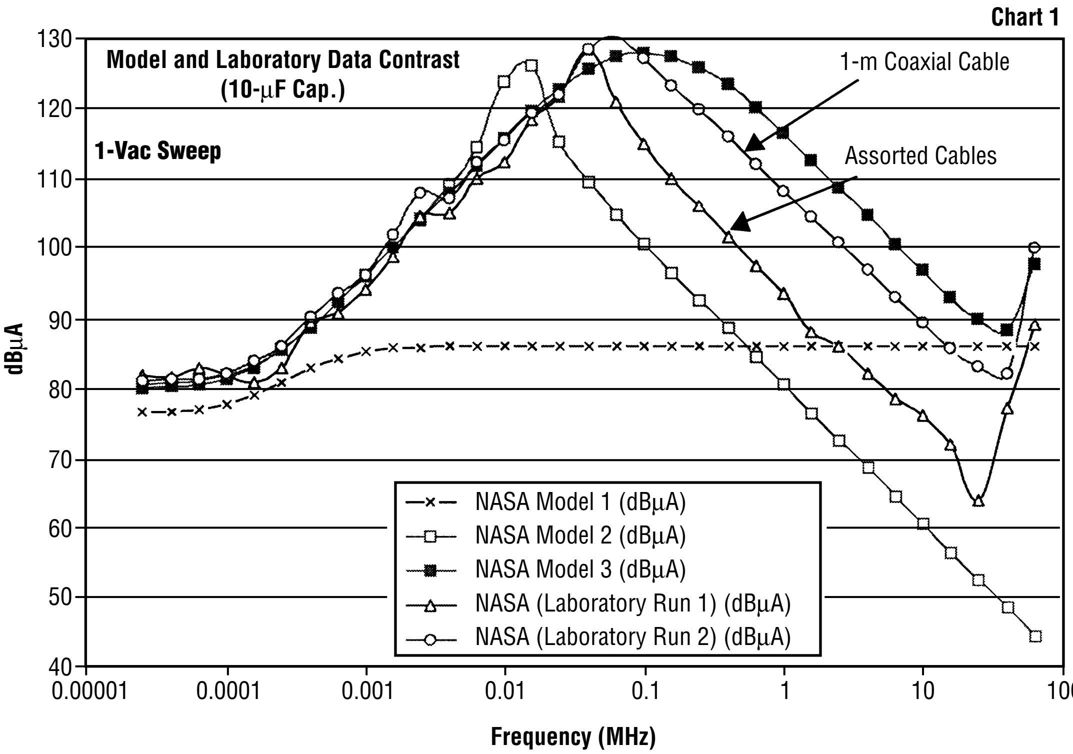
B.1 Contrast of PSpice Simulations (Modeled Data) and Actual Laboratory Data

The following paragraphs contain details and observations regarding the four EMI test setups under consideration. Specifically, these notes pertain to the models that were developed and how they compare to actual data generated in the laboratory.

B.2 NASA CE01 and CE03 (10-μF Capacitor)

Figure 14 contains data from PSpice models and actual laboratory data for the 10-μF capacitor. Model 1 was constructed with the Z_s resistor in series with the frequency generator's output. Note that the current is ≤86 dBμA and that there is very little relationship to the laboratory data at frequencies >1 kHz. Model 2 (with Z_s in parallel to the output) generates a curve, which rises to a peak and then drops off at a rate similar to the laboratory results. However, model 2 fails to follow the laboratory data at frequencies >25 MHz. Model 3 contains some aspects of a transmission line incorporated into the model. The model, though not perfect, has most of the characteristics as the laboratory data, especially for the 1-m coaxial cable setup.

Two test setups were used: one contained a 1-m coaxial cable and the other contained an assortment of 1- to 1.5-m banana leads. For both cable types, the data were similar for frequencies <0.1 MHz; but for frequencies >0.1 MHz, the data quickly diverged by as much as 15 dBμA. Despite the difference between the two cables, both curves had similar attributes.



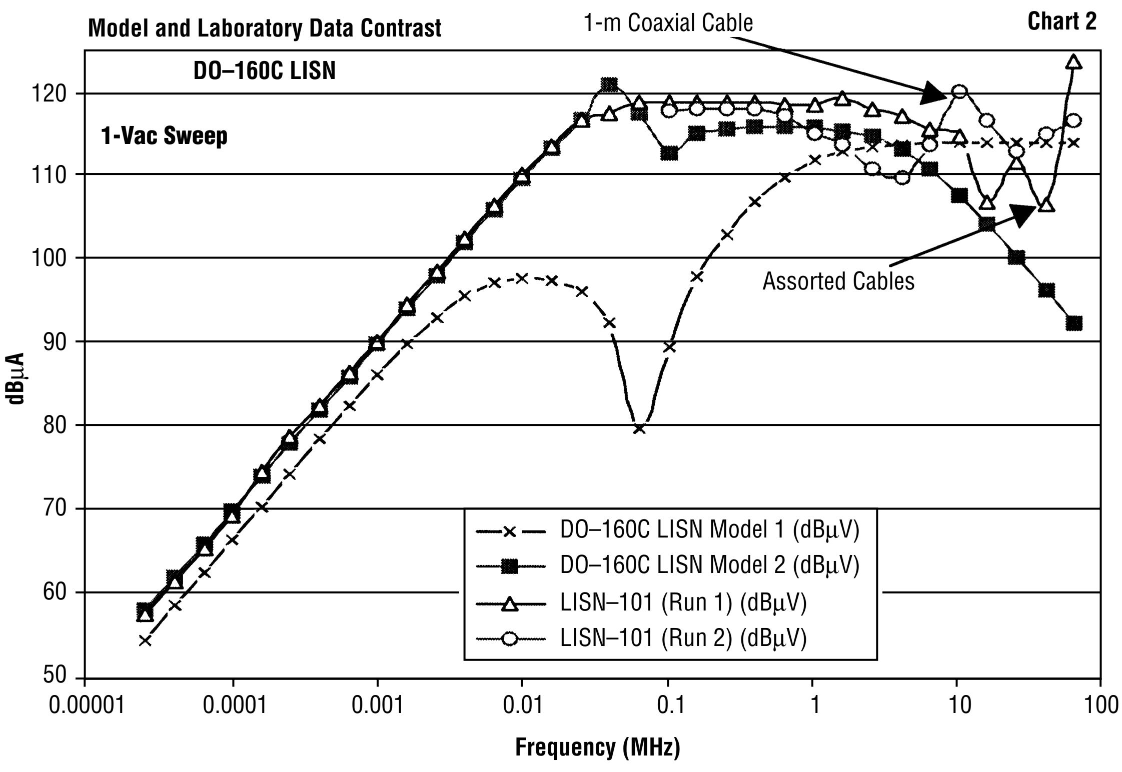
NASA Model 1 (dBµA):	The first of three PSpice models involving the 10-µF capacitor.
NASA Model 2 (dBµA:	The second of three PSpice models involving the 10-µF capacitor, this time with Z_s (50 Ω) in parallel to the EUT and inductance values provided for the leads.
NASA Model 3 (dBµA):	The third of three PSpice models. Much like model 2, but taking into account transmission line characteristics.
NASA (Laboratory Run 1) (dBµA):	Laboratory data involving the 10-µF capacitor. Connection between the EUT and the capacitor contains assorted banana leads.
NASA (Laboratory Run 2) (dBµA):	Laboratory data involving the 10-µF capacitor. Connection between the EUT and the capacitor contains 1-m coaxial cable.

Figure 14. NASA setup with 10-µF capacitor PSpice simulation (modeled data) and laboratory data.

B.3 DO–160C Line Impedance Stabilization Network

Figure 15 contains data from PSpice models and actual laboratory data for the DO–160C LISN. Model 1 was constructed with the Z_s resistor in series with the frequency generator's output. There is a relationship between the model and laboratory data up to ≈8 kHz. However, there is a very dramatic 15-dBμV dip in the model at ≈63 kHz, which is not seen in the laboratory data. In model 2 (with Z_s in parallel to the output), there is a strong relationship between the modeled data and the laboratory data at frequencies approximately ≤50 kHz. However, model 2 fails to follow the laboratory data at frequencies >50 kHz.

Two test setups were used, one contained a 1-m coaxial cable and the other contained an assortment of 1- to 1.5-m banana leads. The data were similar for frequencies <1 MHz; but for frequencies >1 MHz, the two cables performed differently.



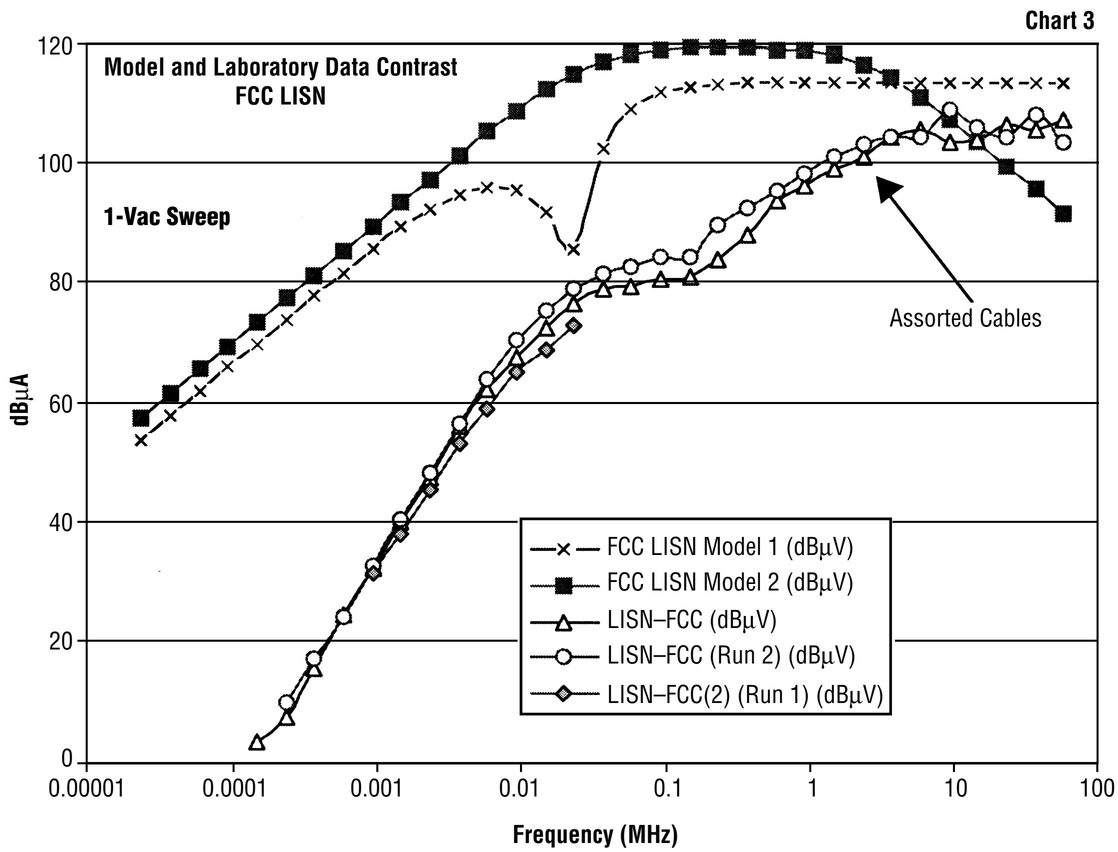
DO–160C LISN Model 1 (dBμV):	The first of two PSpice models involving the DO–160C LISN.
DO–160C LISN Model 2 (dBμV):	The second of two PSpice models involving the DO–160C LISN, this time with Z_s (50 Ω) in parallel to the EUT and inductance values provided for the leads.
LISN–101 (Run 1) (dBμV):	Laboratory data involving the DO–160C LISN. Connection between the EUT and the capacitor contains assorted banana lead cables.
LISN–101 (Run 2) (dBμV):	Laboratory data involving the DO–160C LISN. Connection between the EUT and the capacitor contains 1-m coaxial cable banana leads.

Figure 15. DO–160C LISN setup PSpice simulation (modeled data) and laboratory data.

B.4 FCC Line Impedance Stabilization Network

Figure 16 contains data from PSpice models and actual laboratory data for the FCC LISN. Model 1 was constructed with the Z_s resistor in series with the frequency generator's output. There is a very dramatic 15-dBμV dip in the model at ≈25 kHz, which is not seen in the laboratory data. In model 2 (with Z_s in parallel to the output), there appears to be some relationship between model 2 and the laboratory data to approximately ≤1 MHz. However, it was immediately evident that the laboratory data results were much lower in magnitude than the model. This behavior was not seen for any of the other LISN's. Consequently, the test was rerun (run 2) to gather more information. Similar results were obtained for run 2. Another FCC LISN was selected (LISN–FCC(2)) and data were gathered between 1 and 25 kHz. Once again, the laboratory data resembled the previous two runs, falling far below model 2.

The test setup containing the 1-m coaxial cable was not run for this LISN. Instead, a typical 120-Vac power cord was used because the LISN was constructed to accept a cable of this sort.



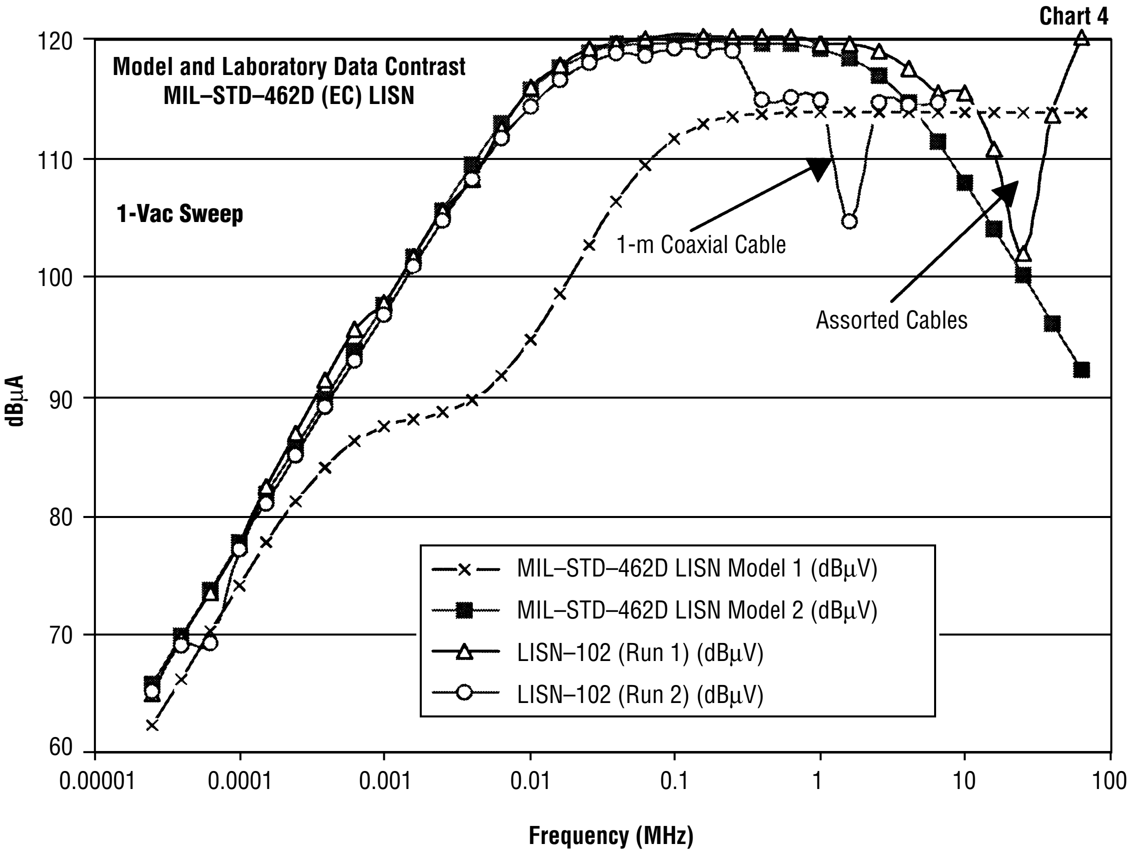
FCC LISN Model 1 (dBμV):	The first of two PSpice models involving the FCC LISN.
FCC LISN Model 2 (dBμV):	The second of two PSpice models involving the FCC LISN, this time with Z_s (50 Ω) in parallel to the EUT and inductance values provided for the leads.
LISN–FCC (dBμV):	Laboratory data involving the FCC LISN. Connection between the EUT and the capacitor contains assorted banana lead cables.
LISN–FCC (Run 2) (dBμV):	Laboratory data involving the FCC LISN. Connection between the EUT and the capacitor contains assorted banana lead cables. This was a rerun of the previous test to verify laboratory data.
LISN-FCC(2) (Run 1) (dBμV):	Laboratory data involving the FCC LISN. Connection between the EUT and the capacitor contains assorted banana lead cables. This was another, but similar LISN to further verify laboratory data.

Figure 16. FCC LISN setup PSpice simulation (modeled data) and laboratory data.

B.5 European Community Line Impedance Stabilization Network (MIL–STD–462D LISN)

Figure 17 contains data from PSpice models and actual laboratory data for the EC LISN. Model 1 was constructed with the Z_s resistor in series with the frequency generator's output. There is some relationship between the model and laboratory data approximately ≤1 MHz. In model 2 (with Z_s in parallel to the output), there is a stronger relationship between the modeled data and the laboratory data at frequencies up to approximately ≤25 MHz. However, model 2 fails to follow the laboratory data at frequencies >25 MHz.

Two test setups were used, one contained a 1-m coaxial cable and the other contained an assortment of 1- to 1.5-m banana leads. The data were similar for frequencies <250 kHz, but for frequencies >250 kHz, the two cables performed differently.



Note: EC LISN = MIL–STD–462D LISN

MIL–STD–462D LISN Model 1 (dBμV):	The first of two PSpice models involving the MIL–STD–462D LISN.
MIL–STD–462D LISN Model 2 (dBμV):	The second of two PSpice models involving the MIL–STD–462D LISN, this time with Z_s (50 Ω) in parallel to the EUT and inductance values provided for the leads.
LISN–102 (Run 1) (dBμV) :	Laboratory data involving the MIL–STD–462D LISN. Connection between the EUT and the capacitor contains assorted banana lead cables.
LISN–102 (Run 2) (dBμV) :	Laboratory data involving the MIL–STD–462D LISN.

Figure 17. EC LISN setup PSpice simulation (modeled data) and laboratory data.

APPENDIX C—EQUIPMENT LIST

Table 4 shows the equipment used.

Table 4. List of test equipment.

Item	Characteristics	Manufacturer	Model No.	Serial No.	Calibration Due
RF Capacitor	10 μF	Solar Electronics	6512–106R	CAP101	No calibration required
5 μH LISN	DO–160, 100 kHz–	R&B Operations	LISN–101	971103	2–11–00
50 μH LISN	461D/CE, 10 kHz–65 MHz	R&B Operations	LISN–102	970602	2–11–00
50 μH Dual LISN	FCC, 10 kHz–50 MHz	Solar Electronics	8012–50–R–24–BNC	927237	2–19–00
50 μH Dual LISN	FCC, 10 kHz–50 MHz	Solar Electronics	28012–50–R–12–BNC	807–44	2–19–00
Attenuator	20 dB, 20 W	JFW	50FHC–020–20	N/A	No calibration required
Attenuator	20 dB, 20 W	Pasternack	PE 7025–20	N/A	No calibration required
Network/Spectrum Analyzer	10 Hz–500 MHz	Hewlett-Packard	4195A	2904J03407	4–20–00
Spectrum Analyzer	100 Hz–26.5 GHz	Advantest	R3271A	J000312	1–11–00
Current Probe	20 Hz–50 kHz	Electro-Metrics	PCL–10/11	1010	5–18–00
Current Probe	10 kHz–100 MHz	EG&G	SCP I(3)	25	5–3–00
Function Generator	15 MHz	Hewlett-Packard	33120A	US36031287	3–1–00
Signal Generator	500 kHz–1024 MHz	Hewlett-Packard	8640B	2044A–15114	2–25–00
Synthesized Function Generator	30 MHz	Stanford Research	DS345	18093	5–12–00
RF Amplifier	10 kHz–250 MHz	Amplifier Research	10A250	7047	No calibration required
RF Amplifier	10 kHz–220 MHz	Amplifier Research	75A200	18126	No calibration required
Audio Amplifier	20 Hz–50 kHz	Crown	M–600	150	No calibration required
Load Resistor	100 Ω ± 5%	Carborundum Co.	1028AS101–JDS	9037	No calibration required
Load Resistor	56 Ω ± 20%	Cesiwid, Inc.	886AS560–LDS	72819	No calibration required

APPENDIX D—MATHEMATICA COMPUTER CODE AND RUNS FOR FINDING VARIOUS TRANSFER FUNCTIONS

Table 5 provides decibel limits in the NASA CE01 and the EC (actually IEC) standards at various frequencies. The fifth column is the difference between the NASA and the EC columns; i.e., NASA-EC values. The sixth column is the TF found by Mathematica for relating the two. The last column is the predicted NASA limit by adding the TF decibels into the CE limit. Hence, the last column compares with the second column and shows a good comparison in this and all other cases.

Table 5. NASA CE01 (30 Hz to 15 kHz) to EC LISN comparison data table and TF constants.

Frequency (Hz)	Model 3 NASA CE01 (dBμA) (Actual Values)	Model 2 EC LISN (dBμV)	log (*f*)	NASA–EC	TF	EC + TF (dBμA) (Predicted Values)
25.12	80.07	65.48	1.4	14.59	14.56	80.04
39.81	80.23	69.48	1.6	10.75	10.82	80.30
63.10	80.60	73.48	1.8	7.12	7.06	80.53
100.00	81.41	77.48	2.0	3.93	3.87	81.35
158.49	82.96	81.48	2.2	1.48	1.51	82.99
251.19	85.39	85.48	2.4	–0.08	–0.03	85.45
398.11	88.57	89.48	2.6	–0.90	–0.90	88.57
630.96	92.20	93.47	2.8	–1.28	–1.31	92.16
1000.00	96.04	97.46	3.0	–1.43	–1.45	96.01
1584.89	99.97	101.44	3.2	–1.47	–1.48	99.96
2511.89	103.93	105.37	3.4	–1.43	–1.43	103.94
3981.07	107.91	109.17	3.6	–1.27	–1.24	107.93
6309.57	111.86	112.65	3.8	–0.79	–0.77	111.88
10000.00	115.74	115.47	4.0	0.27	0.24	115.71
15848.93	119.47	117.42	4.2	2.04	2.06	119.49
K_0 –162.932	K_1 482.231	K_2 –483.911	K_3 233.379	K_4 –59.2512	K_5 7.62227	K_6 –0.389729

Figure 18 depicts the NASA CE01 and the EC values separately.

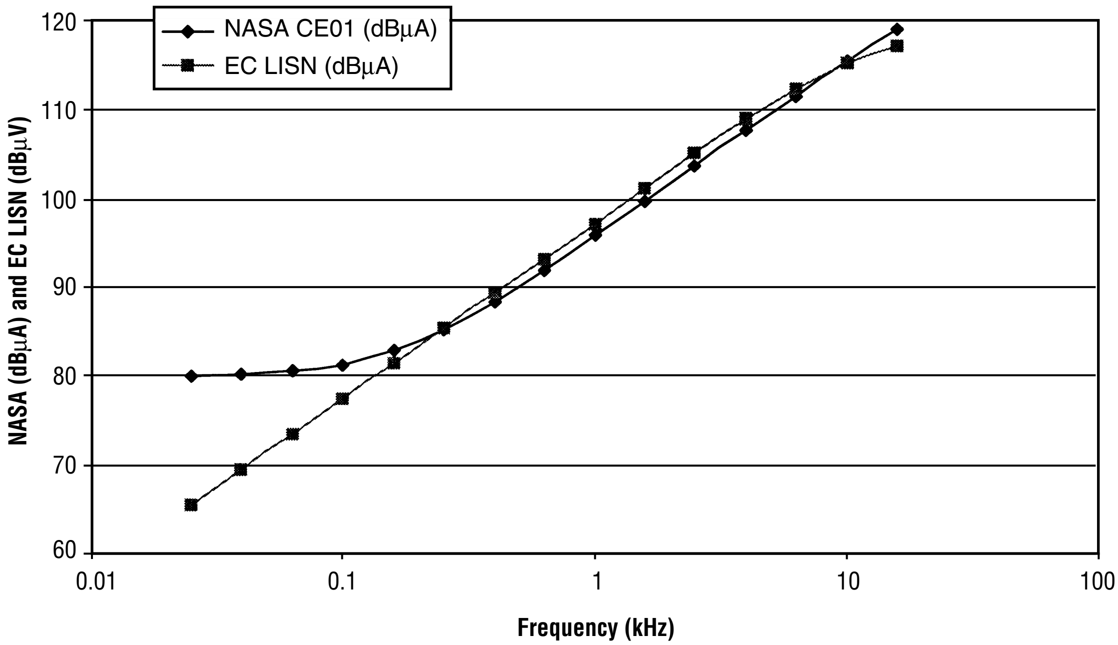


Figure 18. NASA CE01 to EC LISN comparison modeled output response for a 1-Vac signal.

Figure 19 plots the NASA-EC values, both the actual and the TF fit found by Mathematica.

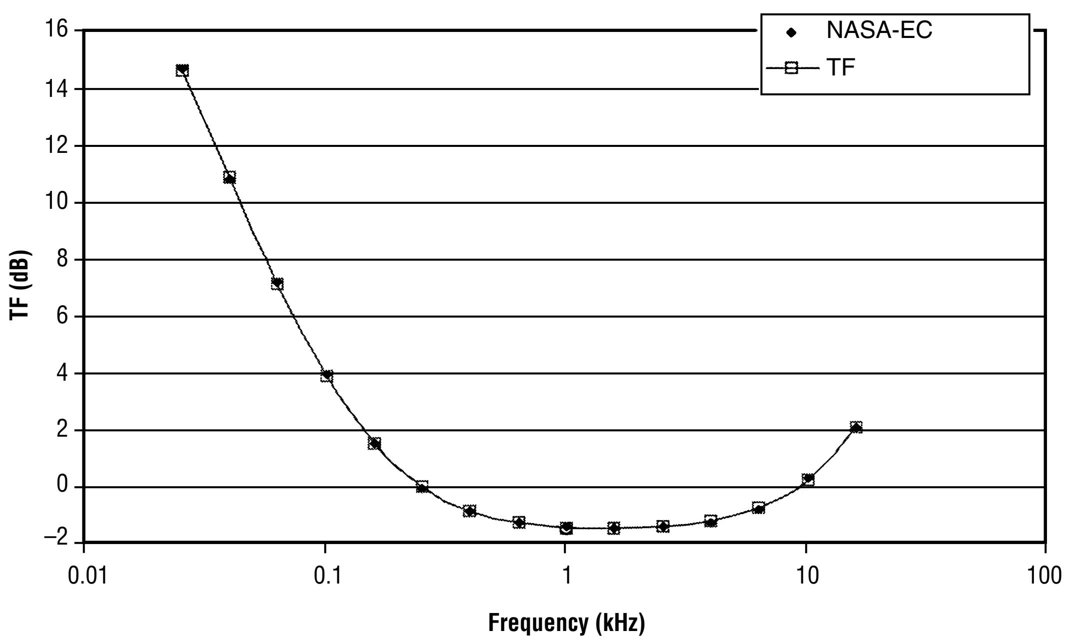


Figure 19. NASA CE01 to EC LISN comparison TF polynomial fit.

Figure 20 plots the actual NASA limits and the predicted NASA limits found by adding the TF decibels into the EC limits.

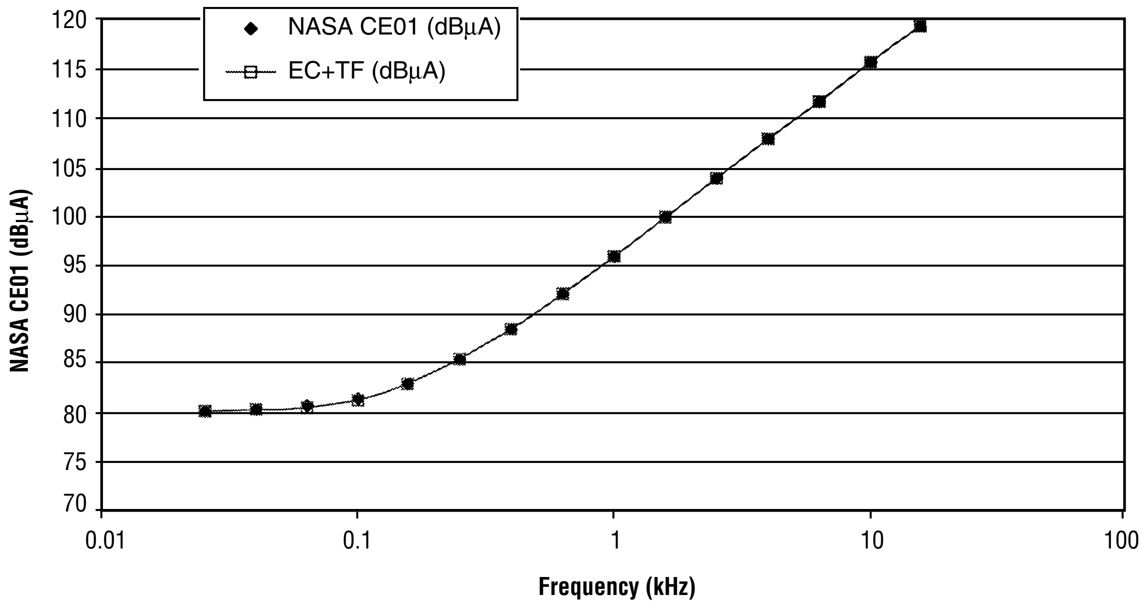


Figure 20. NASA CE01 to EC LISN comparison NASA CE01 prediction from EC LISN data +TF.

Figures 21–24 are prints of the Mathematica input and output for each of the four TF's listed in table 3. The first two groups of words indicate that this run corresponds to the TF for obtaining the NASA results from the EC (IEC) results. Then comes CE01, followed by a number 6 or 5, indicating the order of the polynomial to which this particular run fits the data. The .nb is the file extension used by Mathematica.

After the opening comment lines identifying the run are the input data {(NASA – Commercial dB), Frequency} pairs found from the PSpice simulation results in table 4. The output is merely the confirmation of the input data as registered by the computer for further processing.

The dotted plot is the input data point. All the Mathematica graphs have decibels on the vertical axis and (log *f*) on the vertical axis. The "Fitdata" commands the order of the polynomial to be fitted to the data. By the "Chop" command, the computer discards any polynomial term that is not significant for the desired accuracy and retains the significant terms.

The last expressions in figures 21 and 23 are the best-fitted polynomial with its coefficients.

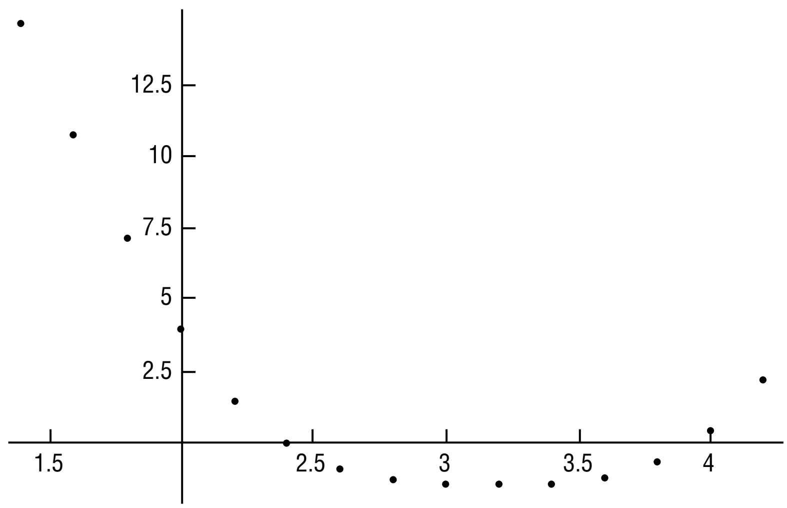
```
NASA-EC-CE01-6.nb                                                    1

(*M.Patel-17 Sept 99 – IIT Research Institute – R&B
Mathematica curve fitting
using the method of least squares*)

data=
  {{1.4, 14.59}, {1.6, 10.75}, {1.8, 7.12}, {2.0, 3.93}, {2.2, 1.48}, {2.4, –0.08}, {2.6, –0.90}, {2.8, –1.28},
   {3.0, –1.43}, {3.2, –1.47}, {3.4, –1.43}, {3.6, –1.27}, {3.8, –0.79}, {4.0, 0.27}, {4.2, 2.04}}

  {{1.4, 14.59}, {1.6, 10.75}, {1.8, 7.12}, {2., 3.93}, {2.2, 1.48}, {2.4, –0.08}, {2.6, –0.9}, {2.8, –1.28},
   {3., –1.43}, {3.2, –1.47}, {3.4, –1.43}, {3.6, –1.27}, {3.8, –0.79}, {4., 0.27}, {4.2, 2.04}}

points = ListPlot [data]
```




```
– Graphics –

Fit [data, {1, x, x^2, x^3, x^4, x^5, x^6}, x]
```

$-162.923 + 482.231x - 483.911x^2 + 233.379x^3 - 59.2512x^4 + 7.62227x^5 - 0.389729x^6$

```
Chop[%]
```

$-162.923 + 482.231x - 483.911x^2 + 233.379x^3 - 59.2512x^4 + 7.62227x^5 - 0.389729x^6$

Figure 21. Display of NASA-EC-CE01-6.nb (screen 1).

Figures 22 and 24 depict two graphs of equation (14). The first graph shows the mathematical fit the computer has found for the given data. The second graph plots the polynomial fit (solid line) and the input data points (dots) superimposed to show the quality of the fit. In all cases, they match very well.

$$\text{NASA Prediction (in dB}\mu\text{A)} = \text{Commercial Value (in dB}\mu\text{V)} + \text{TF} \quad . \tag{13}$$

$$\text{TF} = K_0 + K_1\log(f) + K_2[\log(f)]^2 + K_3[\log(f)]^3 + K_4[\log(f)]^4 + K_5[\log(f)]^5 + K_6[\log(f)]^6 \quad , \tag{14}$$

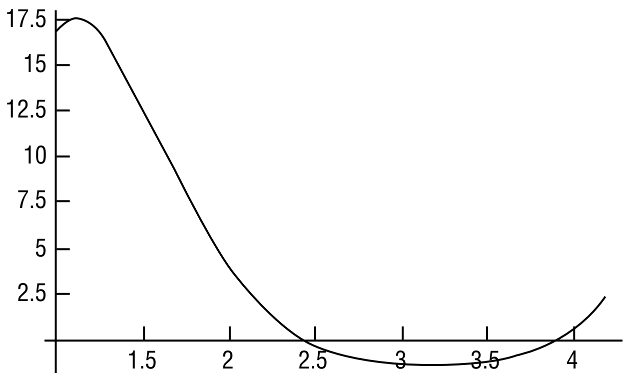
where f is frequency in hertz.

NASA-EC-CE01-6.nb **2**

Chop [%]

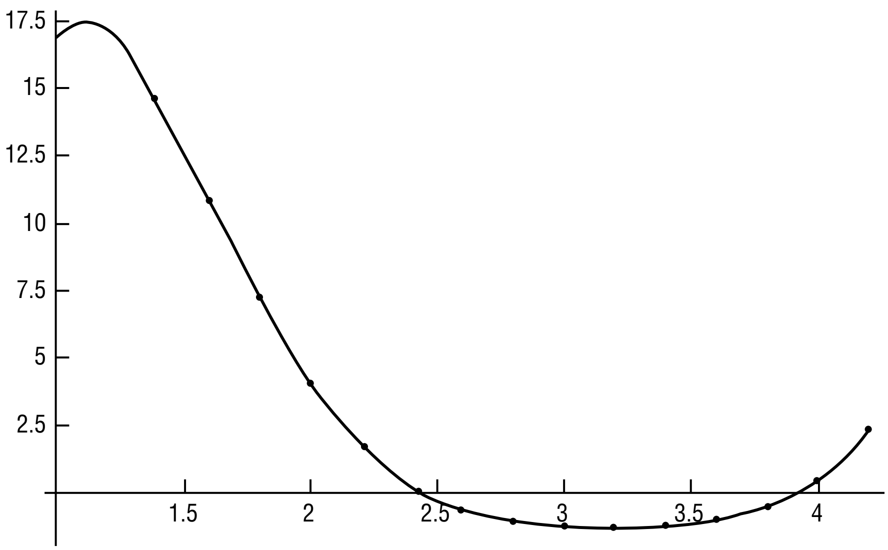
$-162.923 + 482.231x - 483.911x^2 + 233.379x^3 - 59.2512x^4 + 7.62227x^5 - 0.389729x^6$

Plot [%, {x, 1.0, 4.2}]



– Graphics –

Show [%, points]



– Graphics –

NumberForm[–162.923204486418393` + 482.230927342575821`x – 483.911197467275577`x$^2$ + 233.378745512581664`x^3 – 59.251166502166539`x$^4$ + 7.62226580055784275`x^5 – 0.389729173825343799`x^6, 10]

$-162.9232045 + 482.2309273x - 483.9111975x^2 + 233.3787455x^3 - 59.2511665x^4 + 7.622265801x^5 - 0.3897291738x^6$

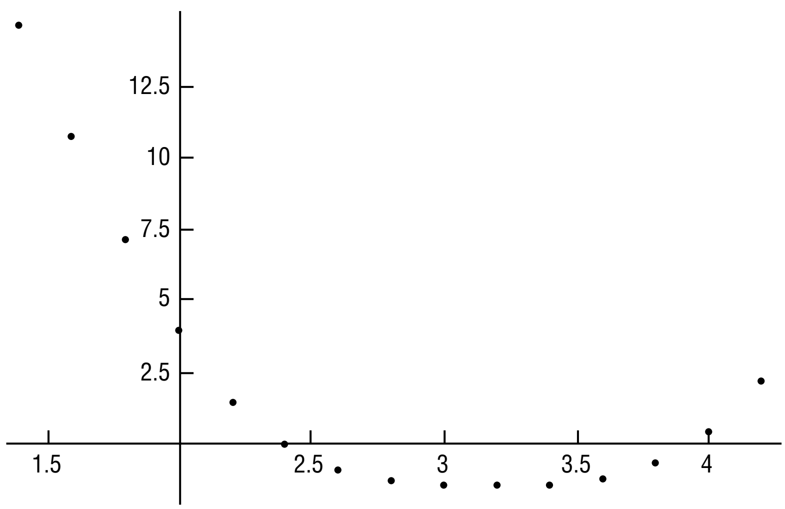
Figure 22. Display of NASA-EC-CE01-6.nb (screen 2).

```
(*M.Patel-17 Sept 99 – IIT Research Institute – R&B
Mathematica curve fitting
using the method of least squares*)
```

```
data= {{1.4, 14.59}, {1.6, 10.75}, {1.8, 7.12}, {2.0, 3.93}, {2.2, 1.48}, {2.4, –0.08}, {2.6, –0.90},
   {2.8, –1.28}, {3.0, –1.43}, {3.2, –1.47}, {3.4, –1.43}, {3.6, –1.27}, {3.8, –0.79}, {4.0, 0.27},
   {4.2, 2.04}}
```

{{1.4, 14.59}, {1.6, 10.75}, {1.8, 7.12}, {2., 3.93}, {2.2, 1.48}, {2.4, –0.08}, {2.6, –0.9},
{2.8, –1.28}, {3., –1.43}, {3.2, –1.47}, {3.4, –1.43}, {3.6, –1.27}, {3.8, –0.79}, {4., 0.27}, {4.2, 2.04}}

```
points = ListPlot [data]
```



– Graphics –

```
Fit [data, {1, x, x^2, x^3, x^4, x^5}, x]
```

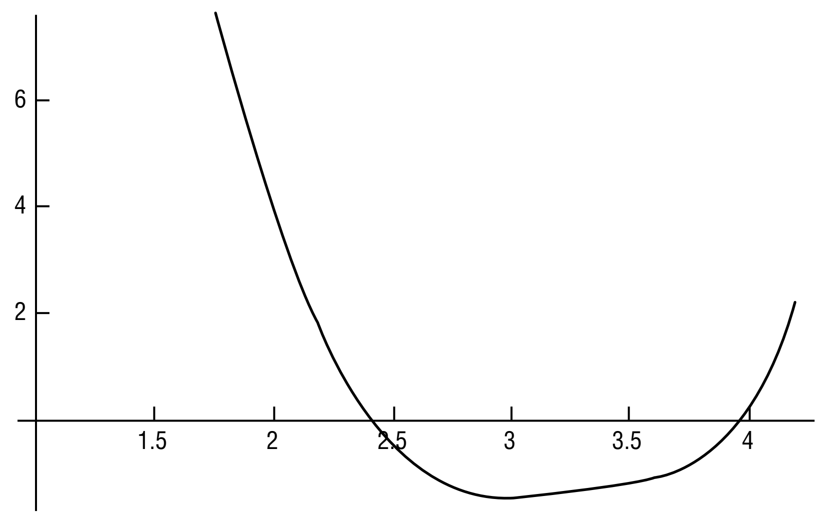
$-38.968 + 175.426x - 177.442x^2 + 75.0495x^3 - 14.5599x^4 + 1.07482x^5$

Figure 23. Display of NASA-EC-CE01-5.nb (screen 1).

Chop [%]

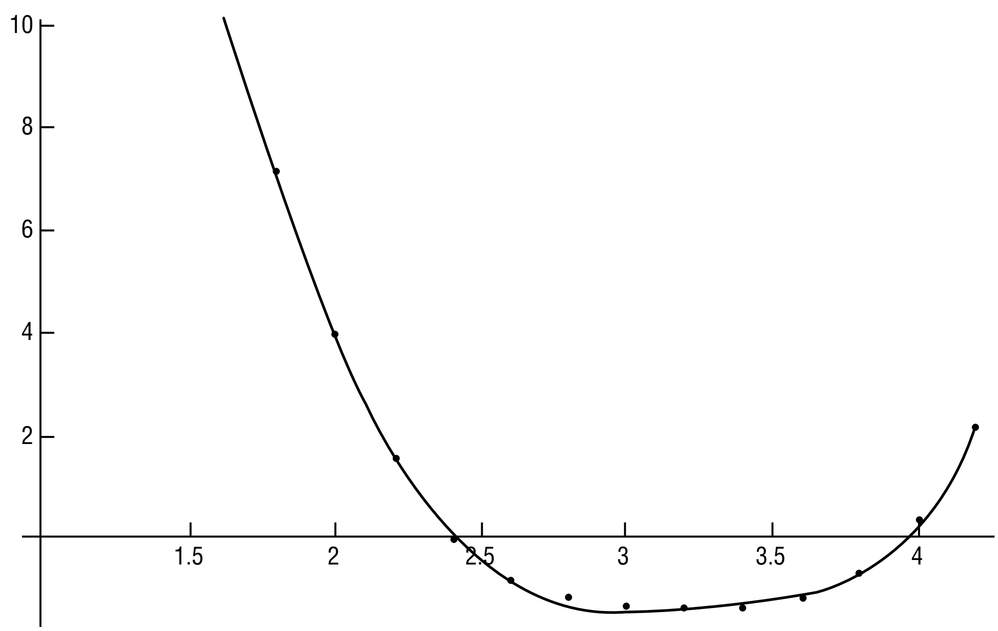
$-38.968 + 175.426x - 177.442x^2 + 75.0495x^3 - 14.5599x^4 + 1.07482x^5$

Plot [%, {x, 1.0, 4.2}]



– Graphics –

Show [%, points)



– Graphics –

Figure 24. Display of NASA-EC-CE01-5.nb (screen 2).

Table 6 provides decibel limits in the NASA CE03 and the FCC standards at various frequencies. The fifth column is the difference between the NASA and the FCC columns; i.e., NASA-FCC values. The sixth column is the TF found by Mathematica for relating the two. The last column is the predicted NASA limit by adding the TF decibels into the FCC limit. Hence, the last column compares with the second column and shows a good comparison in this and all other cases.

Table 6. NASA CE03 (15 kHz to 50 MHz) to FCC LISN comparison data table and TF constants.

Actual Values (Model 3 NASA CE03 column); Predicted Values (FCC + TF column)

Frequency (Hz)	Model 3 NASA CE03 (dBμA)	Model 2 FCC LISN (dBμV)	log (f)	NASA–FCC	TF	FCC + TF (dBμA)
10000	115.74	109.09	4.00	6.66	7.15	116.23
15849	119.47	112.43	4.20	7.04	6.01	118.44
25119	122.85	115.26	4.40	7.59	7.13	122.39
39811	125.56	117.31	4.60	8.25	8.63	125.94
63096	127.31	118.53	4.80	8.77	9.46	128.00
100000	127.95	119.14	5.00	8.81	9.22	128.36
158489	127.50	119.40	5.20	8.11	7.90	127.30
251189	125.96	119.49	5.40	6.47	5.72	125.20
398107	123.40	119.47	5.60	3.92	3.01	122.48
630957	120.11	119.35	5.80	0.76	0.11	119.46
1000000	116.43	119.02	6.00	–2.59	–2.70	116.32
1584893	112.57	118.28	6.20	–5.71	–5.27	113.01
2511886	108.63	116.83	6.40	–8.20	–7.52	109.31
3981072	104.67	114.49	6.60	–9.82	–9.44	105.05
6309573	100.72	111.38	6.80	–10.66	–11.00	100.38
10000000	96.84	107.79	7.00	–10.95	–12.06	95.73
15848932	93.14	103.97	7.20	–10.83	–12.23	91.73
25118864	89.92	100.04	7.40	–10.11	–10.68	89.36
39810717	88.29	96.07	7.60	–7.78	–5.95	90.12
63095734	97.71	92.08	7.80	5.63	4.34	96.42
K_0	K_1	K_2	K_3	K_4	K_5	K_6
27304.34	–29226.03	12879.33	–2992.824	387.2631	–26.49685	0.7499522

Figure 25 depicts the NASA CE03 and the FCC values separately. Figure 26 plots the NASA-FCC values, both the actual and the TF fit found by Mathematica. Figure 27 plots the actual NASA limits and the predicted NASA limits found by adding the TF decibels into the FCC limits.

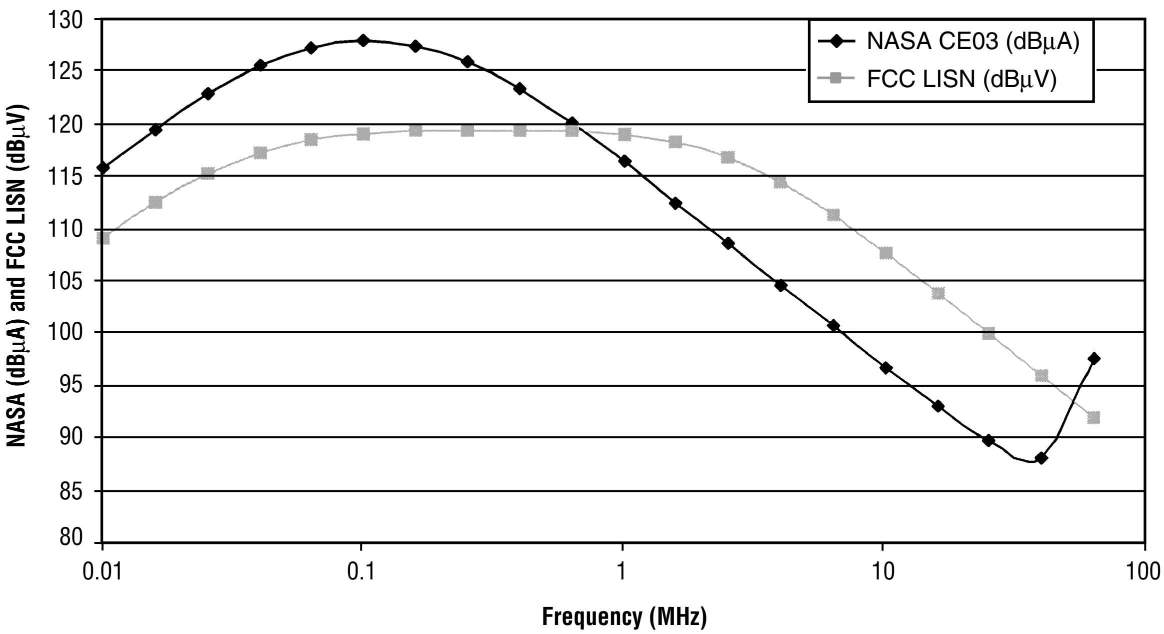


Figure 25. NASA CE03 to FCC LISN comparison modeled output response for a 1-Vac signal.

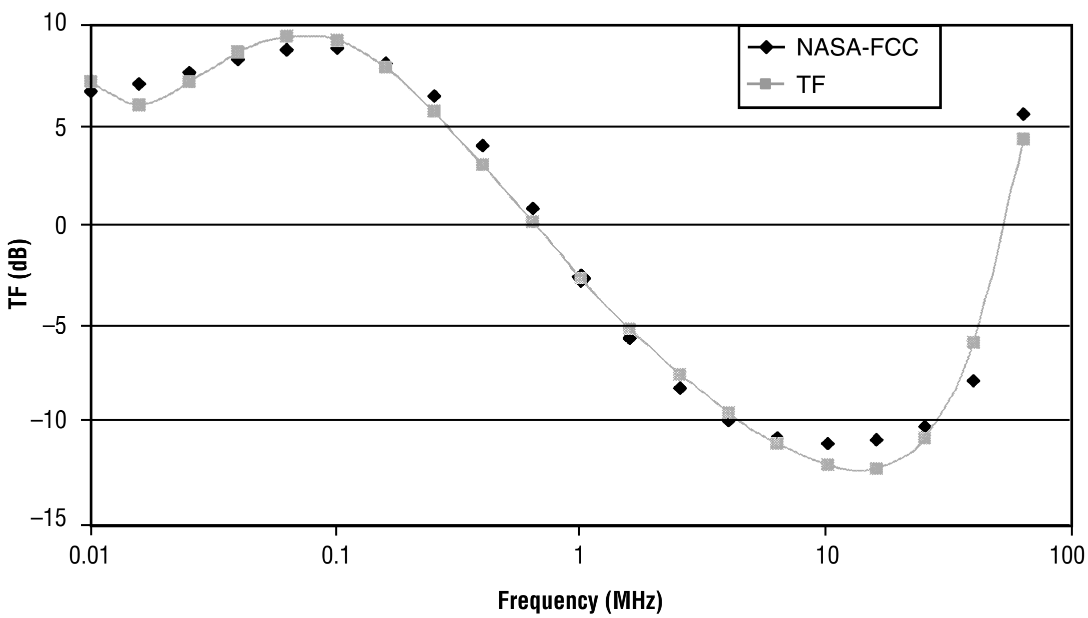


Figure 26. NASA CE03 to FCC LISN comparison TF polynomial fit.

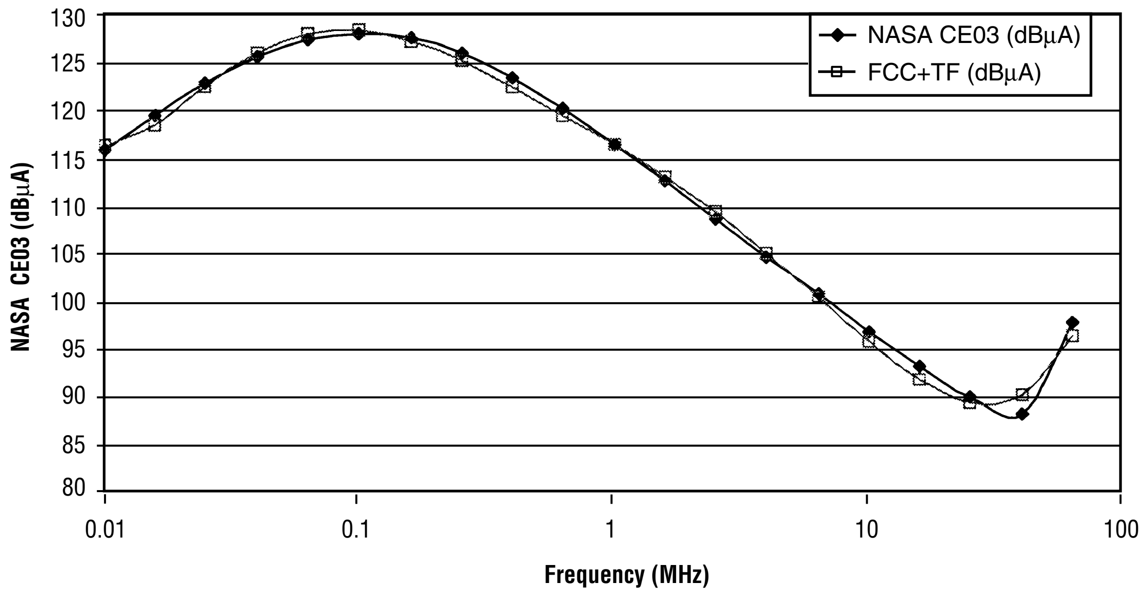


Figure 27. NASA CE03 to FCC LISN comparison NASA CE03 prediction from FCC LISN data +TF.

Figures 28–31 are prints of the Mathematica input and output for each of the four TF's listed in table 3. The first two words indicate that this run corresponds to the TF for obtaining the NASA results from the FCC results. Then comes CE03, followed by number 6 or 5, indicating the order of the polynomial to which this particular run fits the data. The .nb is the file extension used by Mathematica.

After the opening comment lines identifying the run are the input data {(NASA – Commercial dB), Frequency} pairs found from the PSpice simulation results in table 6. The output is merely the confirmation of the input data as registered by the computer for further processing.

The dotted plot is the input data point. All the Mathematica graphs have decibels on the vertical axis and (log *f*) on the vertical axis. The "Fitdata" commands the order of the polynomial to be fitted to the data. By the "Chop" command, the computer discards any polynomial term that is not significant for the desired accuracy and retains the significant terms.

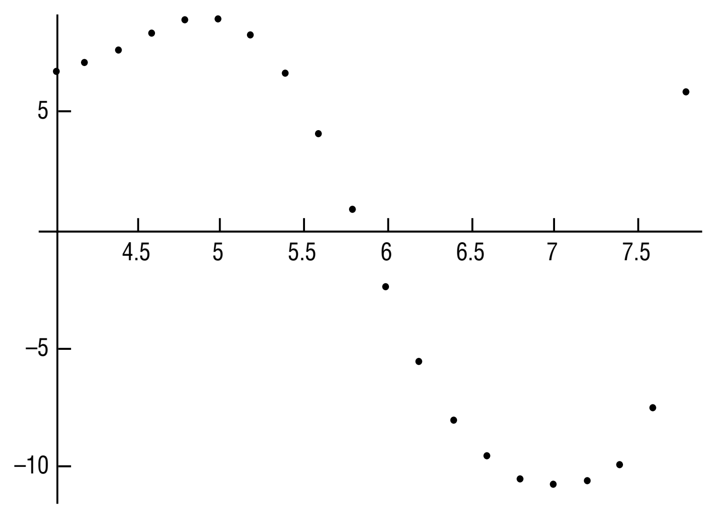
The last expressions in figures 28 and 30 are the best-fitted polynomial with its coefficients.

```
(*M.Patel-17 Sept 99 – IIT Research Institute – R&B
Mathematica curve fitting
using the method of least squares*)

data= {{4, 6.66}, {4.2, 7.04}, {4.4, 7.59}, {4.6, 8.25}, {4.8, 8.77}, {5, 8.81},
  {5.2, 8.11}, {5.4, 6.47}, {5.6, 3.92}, {5.8, 0.76}, {6, –2.59},
  {6.2, –5.71}, {6.4, –8.2}, {6.6, –9.82}, {6.8, –10.66}, {7, –10.95},
  {7.2, –10.83}, {7.4, –10.11}, {7.6, –7.78}, {7.8, 5.63}}

{{4, 6.66}, {4.2, 7.04}, {4.4, 7.59}, {4.6, 8.25}, {4.8, 8.77}, {5, 8.81},
  {5.2, 8.11}, {5.4, 6.47}, {5.6, 3.92}, {5.8, 0.76}, {6., –2.59},
  {6.2, –5.71}, {6.4, –8.2}, {6.6, –9.82}, {6.8, –10.66}, {7, –10.95},
  {7.2, –10.83}, {7.4, –10.11}, {7.6, –7.78}, {7.8, 5.63}}

points = ListPlot [data]
```




```
– Graphics –

Fit [data, {1, x, x^2, x^3, x^4, x^5, x^6}, x]
```

$27304.3 - 29226.x + 12879.3x^2 - 2992.82x^3 + 387.263x^4 - 26.4969x^5 + 0.749952x^6$

Figure 28. Display of NASA-FCC-CE03-6.nb (screen 1).

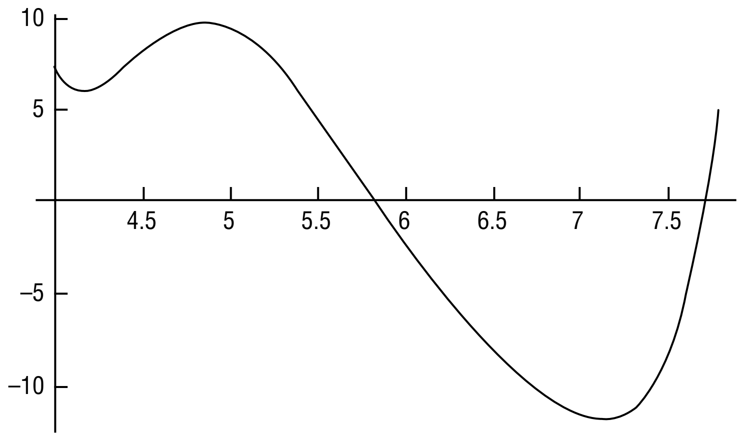
Figures 29 and 31 depict two graphs of equation (14). The first graph shows the mathematical fit the computer has found for the given data. The second graph plots the polynomial fit (solid line) and the input data points (dots) superimposed to show the quality of the fit. In all cases, they match very well.

NASA-FCC-CE03-6.nb **2**

Chop [%]

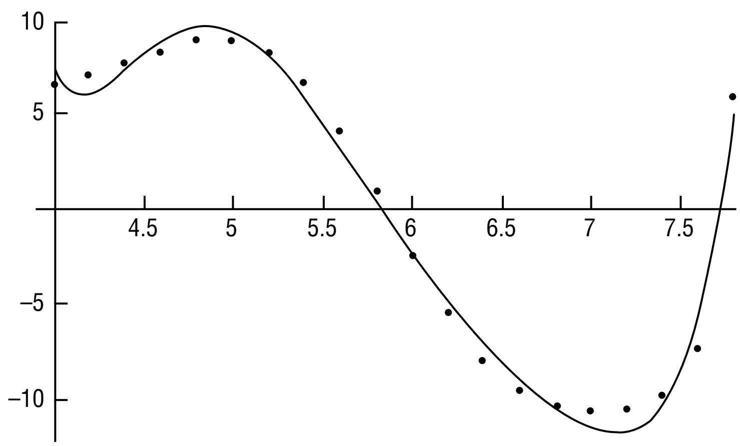
$27304.3 - 29226.x + 12879.3x^2 + 2992.82x^3 + 387.263x^4 - 26.4969x^5 + 0.749952x^6$

Plot [%, {x, 4, 7.8}]



– Graphics –

Show [%, points]



– Graphics –

**NumberForm[27304.34310118929`–
29226.0315148040206`x + 12879.3334712298278`x^2 – 2992.82422564770289`x^3 +
387.263188726484131`x$^4$ – 26.4968528727518171`x^5 + 0.749952274377839245`x^6,
10]**

$27304.3431 - 29226.03151x + 12879.33347x^2 - 2992.824226x^3 + 387.2631887x^4$
$- 26.49685287x^5 + 0.7499522744x^6$

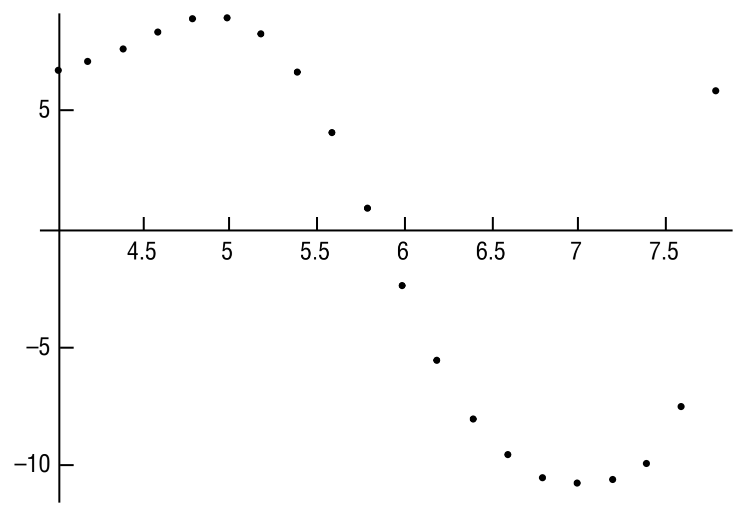
Figure 29. Display of NASA-FCC-CE03-6.nb (screen 2).

(*M.Patel-17 Sept 99 – IIT Research Institute – R&B
Mathematica curve fitting
using the method of least squares*)

```
data=  {{4, 6.66}, {4.2, 7.04}, {4.4, 7.59}, {4.6, 8.25}, {4.8, 8.77},
 {5, 8.81}, {5.2, 8.11}, {5.4, 6.47}, {5.6, 3.92}, {5.8, 0.76}, {6.0, –2.59},
{6.2, –5.71}, {6.4, –8.20}, {6.6, –9.82}, {6.8, –10.66}, {7, –10.95},
{7.2, –10.83}, {7.4, –10.11}, {7.6, –7.78}, {7.8, 5.63}}
```

```
{{4, 6.66}, {4.2, 7.04}, {4.4, 7.59}, {4.6, 8.25}, {4.8, 8.77},
 {5, 8.81}, {5.2, 8.11}, {5.4, 6.47}, {5.6, 3.92}, {5.8, 0.76}, {6., –2.59},
{6.2, –5.71}, {6.4, –8.2}, {6.6, –9.82}, {6.8, –10.66}, {7, –10.95},
{7.2, –10.83}, {7.4, –10.11}, {7.6, –7.78}, {7.8, 5.63}}
```

points = ListPlot [data]



– Graphics –

Fit [data, {1, x, x^2, x^3, x^4, x^5, x^6}, x]

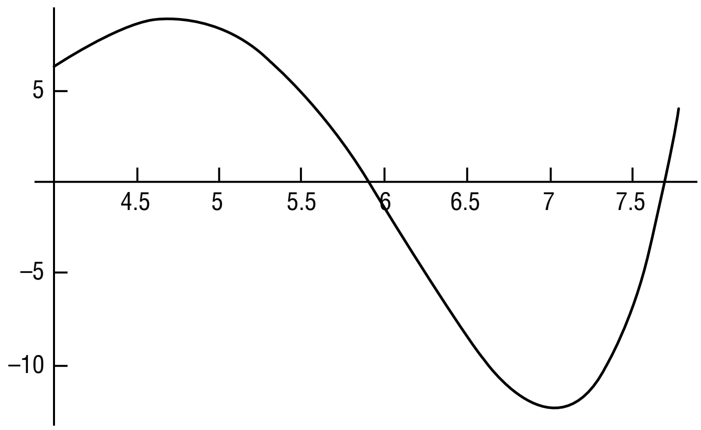
$321.146 - 269.359x + 75.315x^2 - 6.38065x^3 - 0.339417x^4 + 0.0514576x^5$

Figure 30. Display of NASA-FCC-CE03-5.nb (screen 1).

Chop [%]

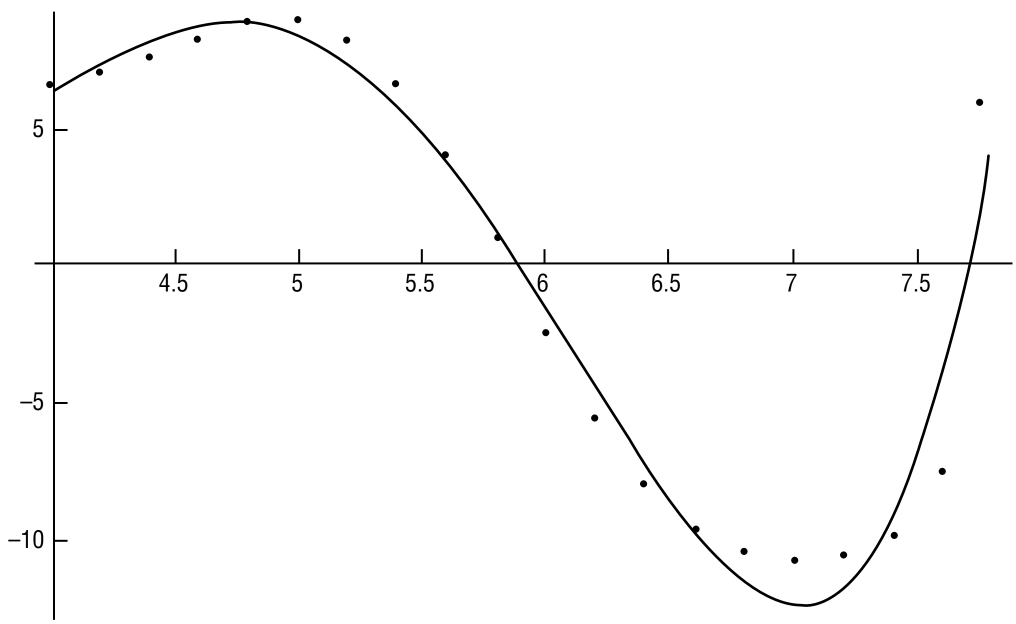
$321.146 - 269.359x + 75.315x^2 - 6.38065x^3 - 0.339417x^4 + 0.0514576x^5$

Plot [%, {x, 4, 7.8}]



– Graphics –

Show [%, points]



– Graphics –

Figure 31. Display of NASA-FCC-CE03-5.nb (screen 2).

Table 7 provides decibel limits in the NASA CE03 and the EC (actually IEC) standards at various frequencies. The fifth column is the difference between the NASA and the EC columns; i.e., NASA-EC values. The sixth column is the TF found by Mathematica for relating the two. The last column is the predicted NASA limit by adding the TF decibels into the CE limit. Hence, the last column compares with the second column and shows a good comparison in this and all other cases.

Table 7. NASA CE03 (15 kHz to 50 MHz) to EC LISN comparison data table and TF constants.

Frequency (Hz)	Model 3 NASA CE03 (dBμA) (Actual Values)	Model 2 EC LISN (dBμV)	log (*f*)	NASA–EC	TF	EC + TF (dBμA) (Predicted Values)
10000	115.74	115.47	4.0	0.27	0.68	116.15
15849	119.47	117.42	4.2	2.04	1.20	118.63
25119	122.85	118.56	4.4	4.29	3.91	122.46
39811	125.56	119.11	4.6	6.45	6.72	125.83
63096	127.31	119.36	4.8	7.95	8.53	127.89
100000	127.95	119.46	5.0	8.49	8.92	128.38
158489	127.50	119.49	5.2	8.01	7.94	127.43
251189	125.96	119.49	5.4	6.47	5.88	125.37
398107	123.40	119.43	5.6	3.96	3.18	122.61
630957	120.11	119.30	5.8	0.82	0.23	119.53
1000000	116.43	118.96	6.0	–2.53	–2.63	116.33
1584893	112.57	118.22	6.2	–5.65	–5.21	113.01
2511886	108.63	116.77	6.4	–8.15	–7.42	109.35
3981072	104.67	114.44	6.6	–9.77	–9.27	105.17
6309573	100.72	111.34	6.8	–10.62	–10.76	100.57
10000000	96.84	107.75	7.0	–10.91	–11.80	95.96
15848932	93.14	103.93	7.2	–10.79	–11.99	91.94
25118864	89.92	100.00	7.4	–10.08	–10.50	89.50
39810717	88.29	96.03	7.6	–7.74	–5.79	90.24
63095734	97.71	92.04	7.8	5.66	4.66	96.70
K_0	K_1	K_2	K_3	K_4	K_5	K_6
30722.04	–33003.68	14574.20	–3389.871	438.6613	–29.99149	0.8476321

Figure 32 depicts the NASA CE03 and the EC values separately. Figure 33 plots the NASA-EC values, both the actual and the TF fit found by Mathematica. Figure 34 plots the actual NASA limits and the predicted NASA limits found by adding the TF decibels into the EC limits.

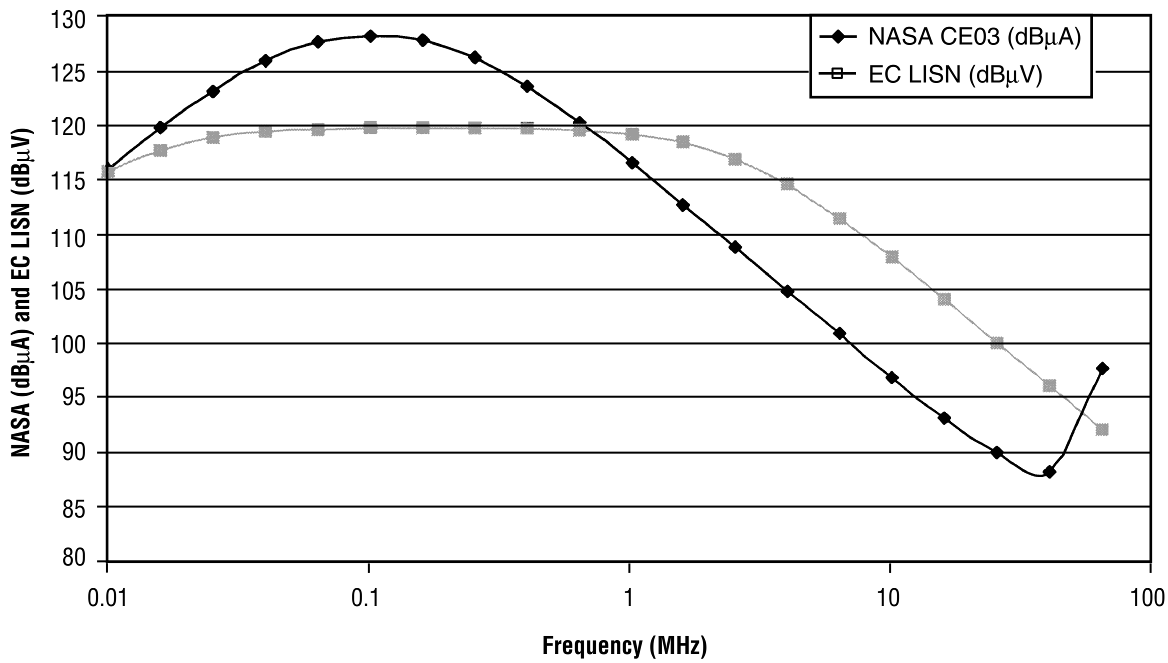


Figure 32. NASA CE03 to EC LISN comparison modeled output response for a 1-Vac signal.

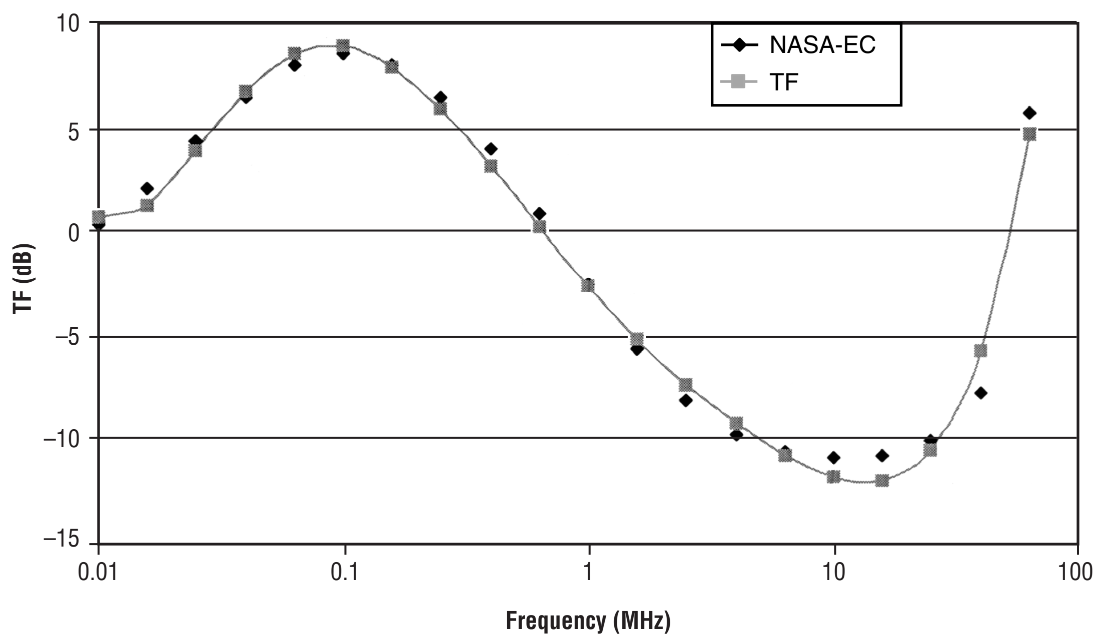


Figure 33. NASA CE03 to EC LISN comparison TF polynomial fit.

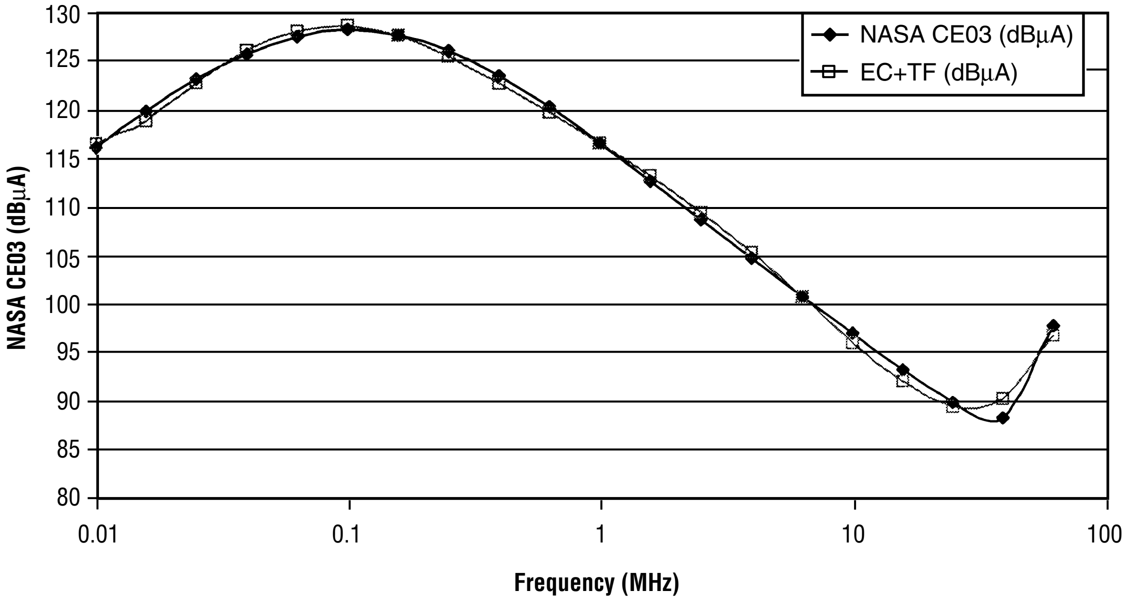


Figure 34. NASA CE03 to EC LISN comparison NASA CE03 prediction from EC LISN data +TF.

Figures 35 through 38 are prints of the Mathematica input and output for each of the four TF's listed in table 3. The first two groups of words indicate that this run corresponds to the TF for obtaining the NASA results from the EC (IEC) results. Then comes CE03, followed by a number 6 or 5, indicating the order of the polynomial to which this particular run fits the data. The .nb is the file extension used by Mathematica.

After the opening comment lines identifying the run are the input data {(NASA – Commercial dB), Frequency} pairs found from the PSpice simulation results in table 7. The output is merely the confirmation of the input data as registered by the computer for further processing.

The dotted plot is the input data point. All the Mathematica graphs have decibels on the vertical axis and (log *f*) on the vertical axis. The "Fitdata" commands the order of the polynomial to be fitted to the data. By the "Chop" command, the computer discards any polynomial term that is not significant for the desired accuracy and retains the significant terms.

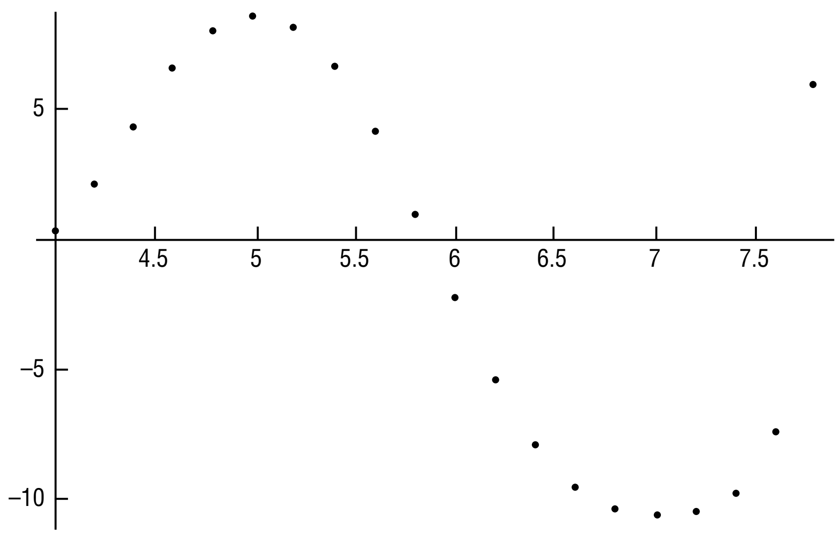
The last expressions in figures 35 and 37 are the best-fitted polynomial with its coefficients.

(*M.Patel-17 Sept 99 – IIT Research Institute – R&B
Mathematica curve fitting
using the method of least squares*)

```
data= {{4.0, 0.27}, {4.2, 2.04}, {4.4, 4.29}, {4.6, 6.45}, {4.8, 7.95},
    {5, 8.49}, {5.2, 8.01}, {5.4, 6.47}, {5.6, 3.96}, {5.8, 0.82}, {6, –2.53},
    {6.2, –5.65}, {6.4, –8.15}, {6.6, –9.77}, {6.8, –10.62}, {7, –10.91},
    {7.2, –10.79}, {7.4, –10.08}, {7.6, –7.74}, {7.8, 5.66}}
```

```
{{4., 0.27}, {4.2, 2.04}, {4.4, 4.29}, {4.6, 6.45}, {4.8, 7.95}, {5, 8.49}, {5.2, 8.01},
    {5.4, 6.47}, {5.6, 3.96}, {5.8, 0.82}, {6, –2.53}, {6.2, –5.65}, {6.4, –8.15},
    {6.6, –9.77}, {6.8, –10.62}, {7, –10.91}, {7.2, –10.79}, {7.4, –10.08},
    {7.6, –7.74}, {7.8, 5.66}}
```

points = ListPlot [data]



– Graphics –

Fit[data, {1, x, x^2, x^3, x^4, x^5, x^6}, x]

$30722. - 33003.7x + 14574.2x^2 - 3389.87x^3 + 438.661x^4 - 29.9915x^5 + 0.847632x^6$

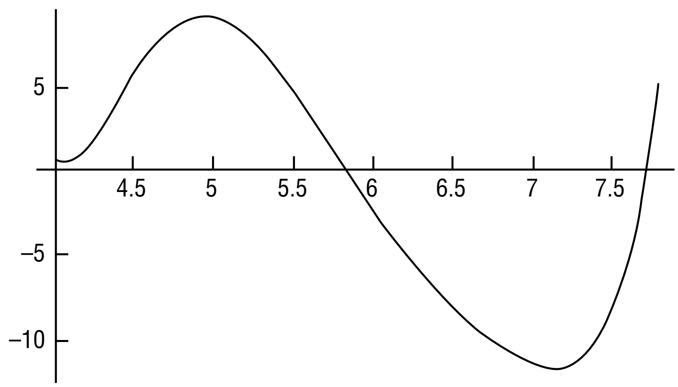
Figure 35. Display of NASA-EC-CE03-6.nb (screen 1).

Figures 36 and 38 depict two graphs of equation (14). The first graph shows the mathematical fit the computer has found for the given data. The second graph plots the polynomial fit (solid line) and the input data points (dots) superimposed to show the quality of the fit. In all cases, they match very well.

Chop[%]

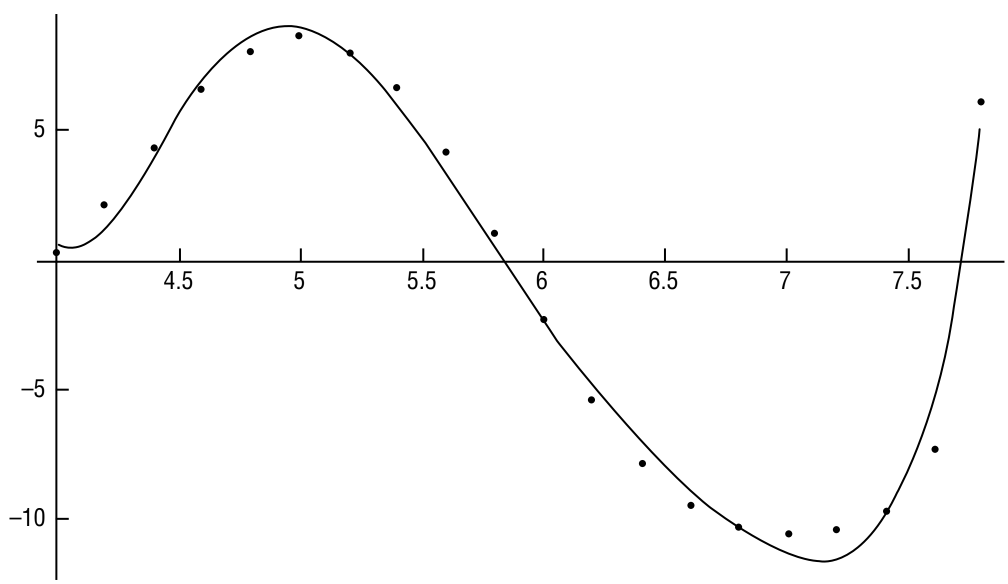
$30722. - 33003.7x + 14574.2x^2 - 3389.87x^3 + 438.661x^4 - 29.9915x^5 + 0.847632x^6$

Plot[%, {x, 4, 7.8}]



– Graphics –

Show[%, points]



– Graphics –

NumberForm[30722.0427166787946`– 33003.680129285855`x + 14574.2024160770311`x^2 – 3389.87107808538601`x^3 + 438.661351510341646`x^4 – 29.9914969238839201`x^5 + 0.847632184889482509`x^6, 10]

$30722.04272 - 33003.68013x + 14574.20242x^2 - 3389.871078x^3 + 438.6613515x^4 - 29.99149692x^5 + 0.8476321849x^6$

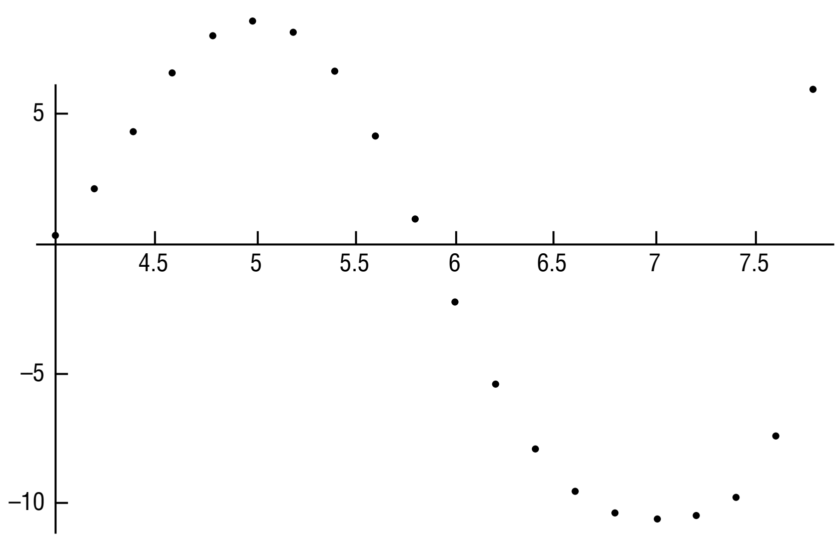
Figure 36. Display of NASA-EC-CE03-6.nb (screen 2).

```
(*M.Patel-17 Sept 99 – IIT Research Institute – R&B
Mathematica curve fitting
using the method of least squares*)
```

```
data= {{4.0, 0.27}, {4.2, 2.04}, {4.4, 4.29}, {4.6, 6.45}, {4.8, 7.95},
    {5, 8.49}, {5.2, 8.01}, {5.4, 6.47}, {5.6, 3.96}, {5.8, 0.82},
    {6, –2.53}, {6.2, –5.65}, {6.4, –8.15}, {6.6, –9.77}, {6.8, –10.62}
    {7, –10.91}, {7.2, –10.79}, {7.4, –10.08}, {7.6, –7.74}, {7.8, 5.66}}
```

```
{{4., 0.27}, {4.2, 2.04}, {4.4, 4.29}, {4.6, 6.45}, {4.8, 7.95},
    {5, 8.49}, {5.2, 8.01}, {5.4, 6.47}, {5.6, 3.96}, {5.8, 0.82},
    {6, –2.53}, {6.2, –5.65}, {6.4, –8.15}, {6.6, –9.77}, {6.8, –10.62}
    {7, –10.91}, {7.2, –10.79}, {7.4, –10.08}, {7.6, –7.74}, {7.8, 5.66}}
```

```
points = ListPlot [data]
```



– Graphics –

```
Fit [data, {1, x, x^2, x^3, x^4, x^5}, x]
```

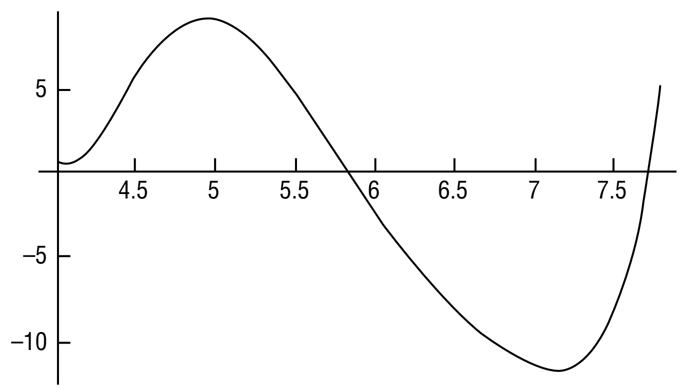
$30722. - 33003.7x + 14574.2x^2 - 3389.87x^3 + 438.661x^4 - 29.9915x^5 + 0.847632x^6$

Figure 37. Display of NASA-EC-CE03-5.nb (screen 1).

Chop [%]

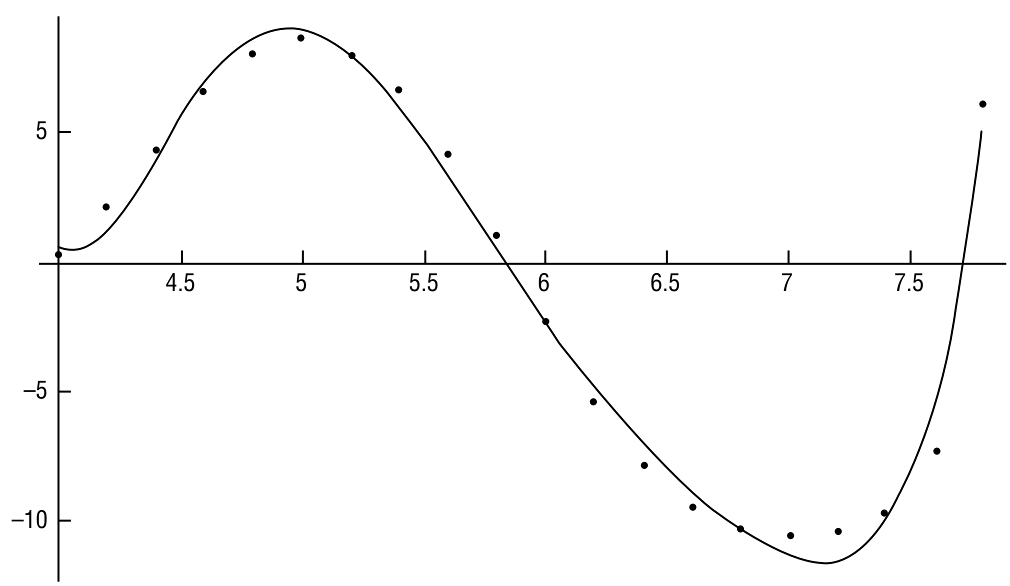
$30722. - 33003.7x + 14574.2x^2 - 3389.87x^3 + 438.661x^4 - 29.9915x^5 - 0.847632x^6$

Plot [%, {x, 4, 7.8}]



– Graphics –

Show [%, points]



– Graphics –

Figure 38. Display of NASA-EC-CE03-5.nb (screen 2).

Table 8 provides decibel limits in the NASA CE03 and the DO–160C standards at various frequencies. The fifth column is the difference between the NASA and the DO columns; i.e., NASA-DO values. The sixth column is the TF found by Mathematica for relating the two. The last column is the predicted NASA limit by adding the TF decibels into the DO limit. Hence, the last column compares with the second column and shows a good comparison in this and all other cases.

Table 8. NASA CE03 (15 kHz to 50 MHz) to DO–160C LISN comparison data table and TF constants.

Frequency (Hz)	Model 3 NASA CE03 (dBμA) (Actual Values)	Model 2 DO–160C LISN (dBμV)	log (f)	NASA–DO	TF	DO + TF (dBμA) (Predicted Values)
10000	115.74	109.57	4.0	6.17	7.30	116.87
15849	119.47	113.21	4.2	6.26	3.81	117.02
25119	122.85	116.61	4.4	6.24	5.33	121.93
39811	125.56	120.67	4.6	4.89	8.46	129.13
63096	127.31	117.29	4.8	10.02	11.19	128.48
100000	127.95	112.70	5.0	15.25	12.53	125.24
158489	127.50	115.01	5.2	12.49	12.23	127.24
251189	125.96	115.62	5.4	10.34	10.45	126.07
398107	123.40	115.81	5.6	7.59	7.62	123.43
630957	120.11	115.83	5.8	4.28	4.24	120.07
1000000	116.43	115.72	6.0	0.71	0.73	116.45
1584893	112.57	115.39	6.2	–2.82	–2.58	112.82
2511886	108.63	114.64	6.4	–6.01	–5.50	109.14
3981072	104.67	113.17	6.6	–8.50	–7.97	105.20
6309573	100.72	110.81	6.8	–10.09	–9.97	100.84
10000000	96.84	107.69	7.0	–10.85	–11.39	96.30
15848932	93.14	104.10	7.2	–10.96	–11.87	92.23
25118864	89.92	100.27	7.4	–10.34	–10.58	89.69
39810717	88.29	96.34	7.6	–8.05	–5.96	90.38
63095734	97.71	92.37	7.8	5.34	4.63	97.00
K_0	K_1	K_2	K_3	K_4	K_5	K_6
42469.69	–44626.91	19304.53	–4404.286	559.7166	–37.62390	1.0465091

Figure 39 depicts the NASA CE03 and the DO values separately. Figure 40 plots the NASA-DO values, both the actual and the TF fit found by Mathematica. Figure 41 plots the actual NASA limits and the predicted NASA limits found by adding the TF decibels into the DO limits.

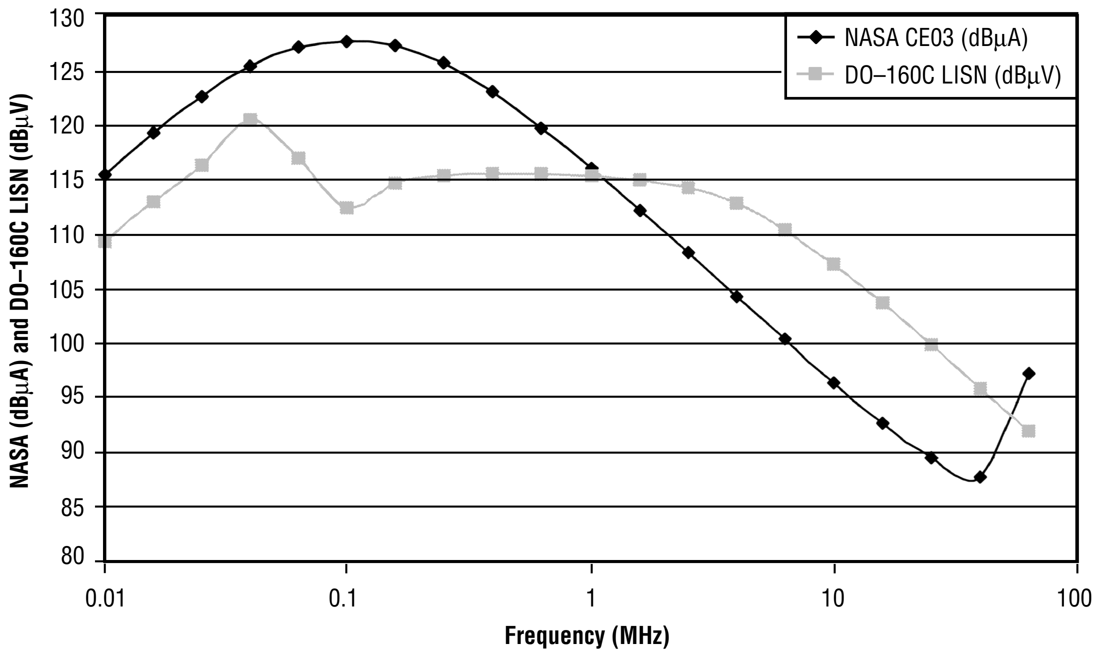


Figure 39. NASA CE03 to DO–160C LISN comparison modeled output response for a 1-Vac signal.

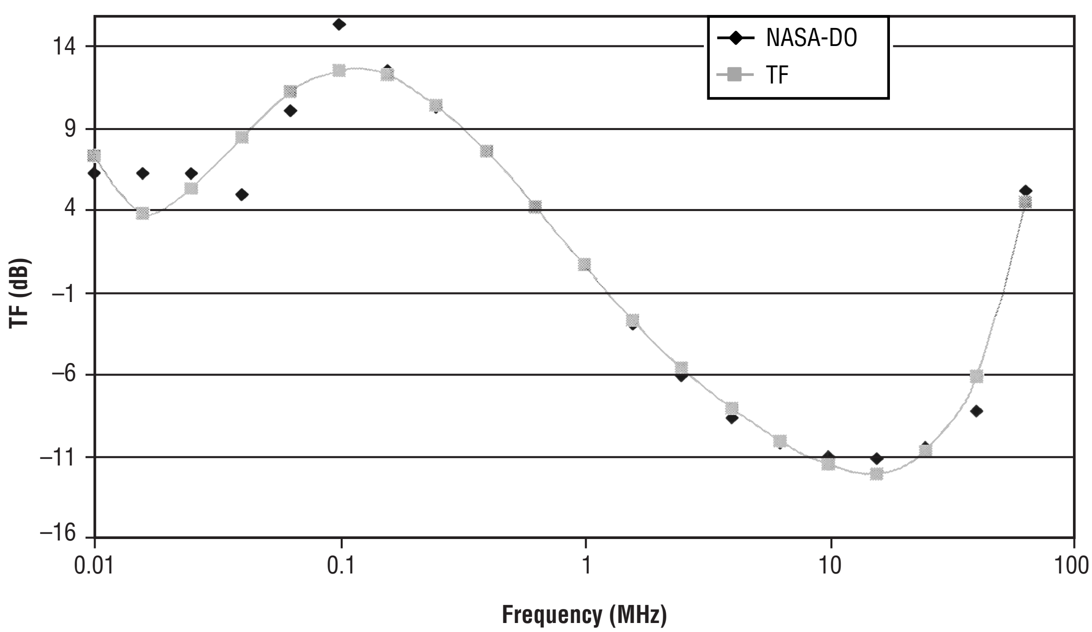


Figure 40. NASA CE03 to DO–160C LISN comparison TF polynomial fit.

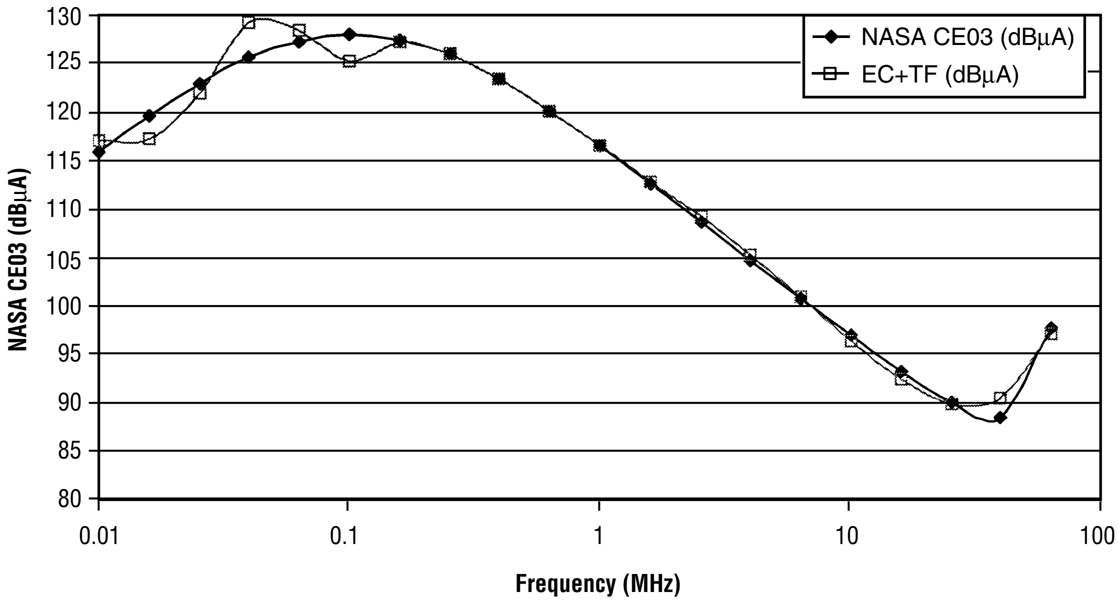


Figure 41. NASA CE03 to DO–160C LISN comparison NASA CE03 prediction from DO–160C LISN data + TF.

Figures 42–45 are prints of the Mathematica input and output for each of the four TF's listed in table 3. The first two groups of words indicate that this run corresponds to the TF for obtaining the NASA results from the DO results. Then comes CE03, followed by a number 6 or 5, indicating the order of the polynomial to which this particular run fits the data. The .nb is the file extension used by Mathematica.

After the opening comment lines identifying the run are the input data {(NASA – Commercial dB), Frequency} pairs found from the PSpice simulation results in table 8. The output is merely the confirmation of the input data as registered by the computer for further processing.

The dotted plot is the input data point. All the Mathematica graphs have decibels on the vertical axis and (log *f*) on the vertical axis. The "Fitdata" commands the order of the polynomial to be fitted to the data. By the "Chop" command, the computer discards any polynomial term that is not significant for the desired accuracy and retains the significant terms.

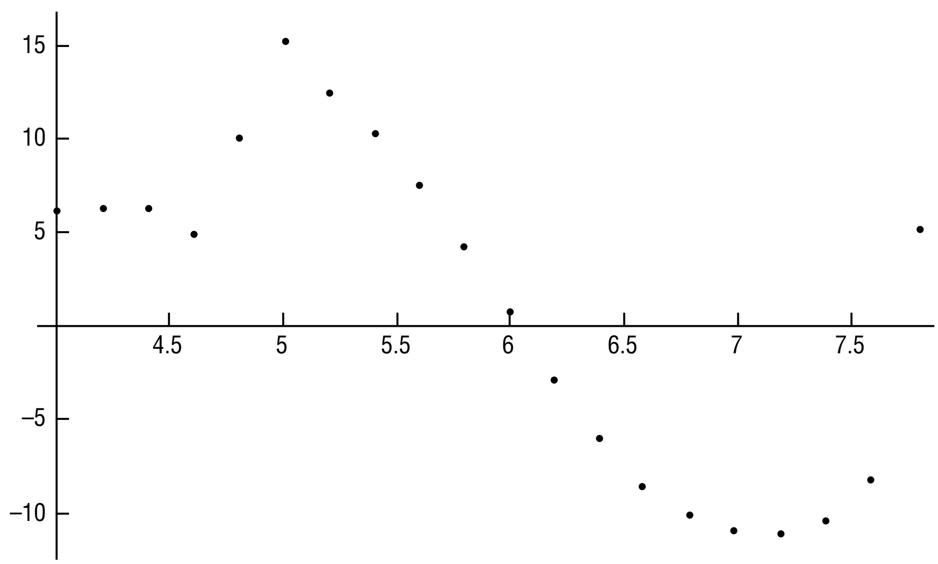
The last expressions in figures 42 and 44 are the best-fitted polynomial with its coefficients.

```
(*M.Patel-17 Sept 99 – IIT Research Institute – R&B
Mathematica curve fitting
using the method of least squares*)

data= {{4, 6.17}, {4.2, 6.26}, {4.4, 6.24}, {4.6, 4.89}, {4.8, 10.02},
    {5, 15.25}, {5.2, 12.49}, {5.4, 10.34}, {5.6, 7.59}, {5.8, 4.28},
    {6, 0.71}, {6.2, –2.82}, {6.4, –6.01}, {6.6, –8.50}, {6.8, –10.09},
    {7, –10.85}, {7.2, –10.96}, {7.4, –10.34}, {7.6, –8.05}, {7.8, 5.34}}

{{4, 6.17}, {4.2, 6.26}, {4.4, 6.24}, {4.6, 4.89}, {4.8, 10.02}, {5, 15.25},
    {5.2, 12.49}, {5.4, 10.34}, {5.6, 7.59}, {5.8, 4.28}, {6, 0.71}, {6.2, –2.82},
    {6.4, –6.01}, {6.6, –8.5}, {6.8, –10.09}, {7, –10.85}, {7.2, –10.96},
    {7.4, –10.34}, {7.6, –8.05}, {7.8, 5.34}}

points = ListPlot [data]
```




```
– Graphics –

Fit [data, {1, x, x^2, x^3, x^4, x^5, x^6}, x]
```

$42469.7 - 44626.9x + 19304.5x^2 - 4404.29x^3 + 559.717x^4 - 37.6239x^5 + 1.04651x^6$

Figure 42. Display of NASA-DO-CE03-6.nb (screen 1).

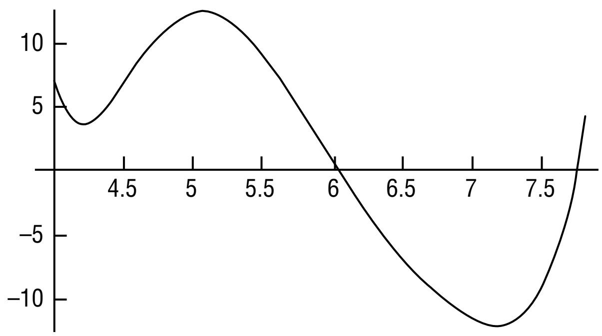
Figures 43 and 45 depict two graphs of equation (14). The first graph shows the mathematical fit the computer has found for the given data. The second graph plots the polynomial fit (solid line) and the input data points (dots) superimposed to show the quality of the fit. In all cases, they match very well.

NASA-DO-CE03-6.nb 2

Chop [%]

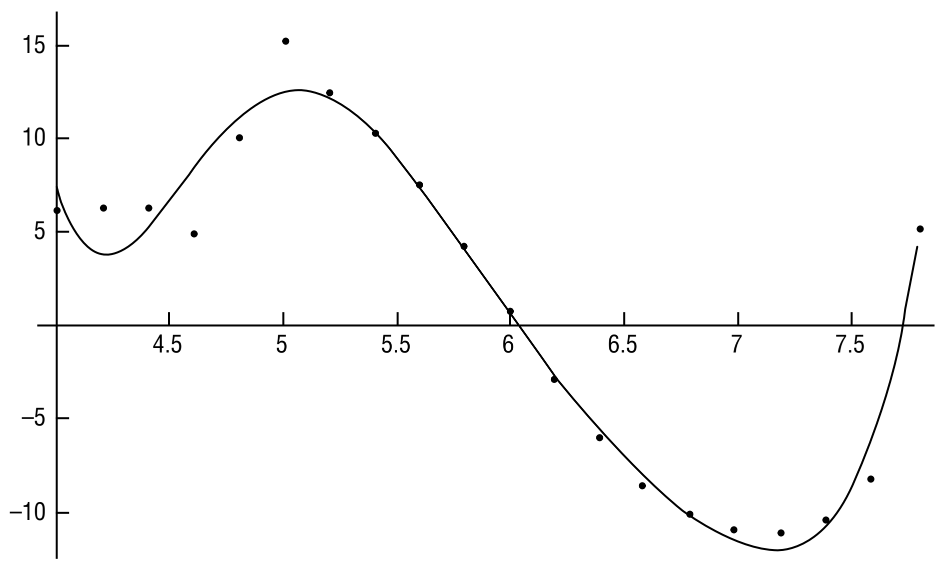
$42469.7 - 44626.9x + 19304.5x^2 - 4404.29x^3 + 559.717x^4 - 37.6239x^5 + 1.04651x^6$

Plot [%, {x, 4, 7.8}]



– Graphics –

Show [%, points]



– Graphics –

```
NumberForm[42469.6785307558588`–
  44626.9086090052802`x + 19304.5311192525446`x^2 – 4404.28596172932707`x^3 +
  559.716574040506653`x^4 – 37.6239045729746512`x^5 + 1.04650911995843709`x^6,
  10]
```

$42469.67853 - 44626.90861x + 19304.53112x^2 - 4404.285962x^3 + 559.716574x^4 - 37.62390457x^5 + 1.04650912x^6$

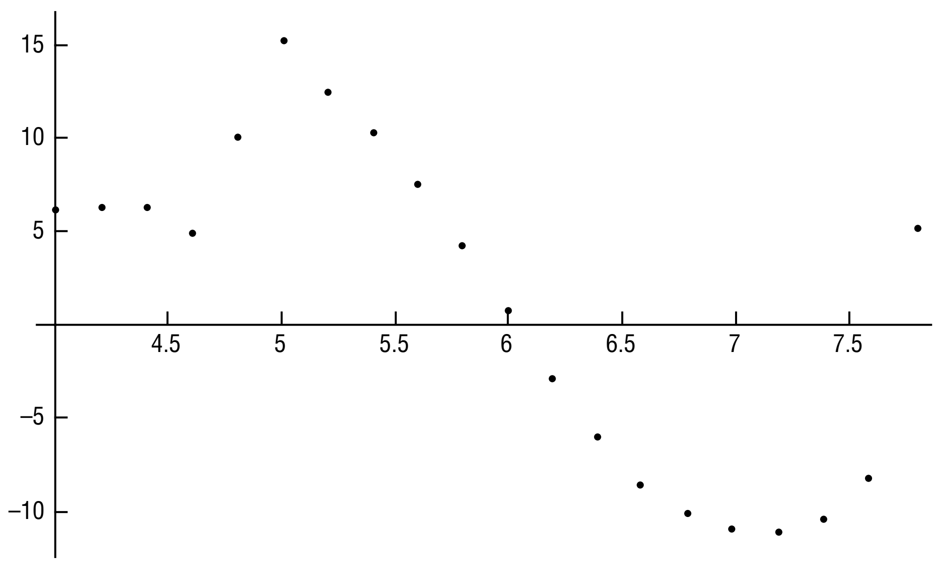
Figure 43. Display of NASA-DO-CE03-6.nb (screen 2).

```
(*M.Patel-17 Sept 99 – IIT Research Institute – R&B
Mathematica curve fitting
using the method of least squares*)

data= {{4, 6.17}, {4.2, 6.26}, {4.4, 6.24}, {4.6, 4.89}, {4.8, 10.02},
    {5, 15.25}, {5.2, 12.49}, {5.4, 10.34}, {5.6, 7.59}, {5.8, 4.28},
    {6, 0.71}, {6.2, –2.82}, {6.4, –6.01}, {6.6, –8.50}, {6.8, –10.09},
    {7, –10.85}, {7.2, –10.96}, {7.4, –10.34}, {7.6, –8.05}, {7.8, 5.34}}

{{4, 6.17}, {4.2, 6.26}, {4.4, 6.24}, {4.6, 4.89}, {4.8, 10.02}, {5, 15.25},
    {5.2, 12.49}, {5.4, 10.34}, {5.6, 7.59}, {5.8, 4.28}, {6, 0.71}, {6.2, –2.82},
    {6.4, –6.01}, {6.6, –8.5}, {6.8, –10.09}, {7, –10.85}, {7.2, –10.96},
    {7.4, –10.34}, {7.6, –8.05}, {7.8, 5.34}}

points = ListPlot [data]
```




```
– Graphics –

Fit [data, {1, x, x^2, x^3, x^4, x^5}, x]
```

$4816.4 - 4219.77x + 1437.36x^2 - 236.9x^3 + 18.8426x^4 - 0.577482x^5$

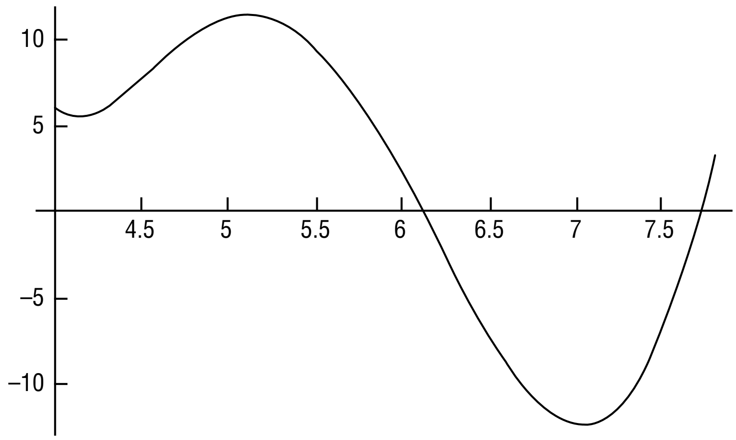
Figure 44. Display of NASA-DO-CE03-5.nb (screen 1).

NASA-DO-CE03-5.nb

Chop [%]

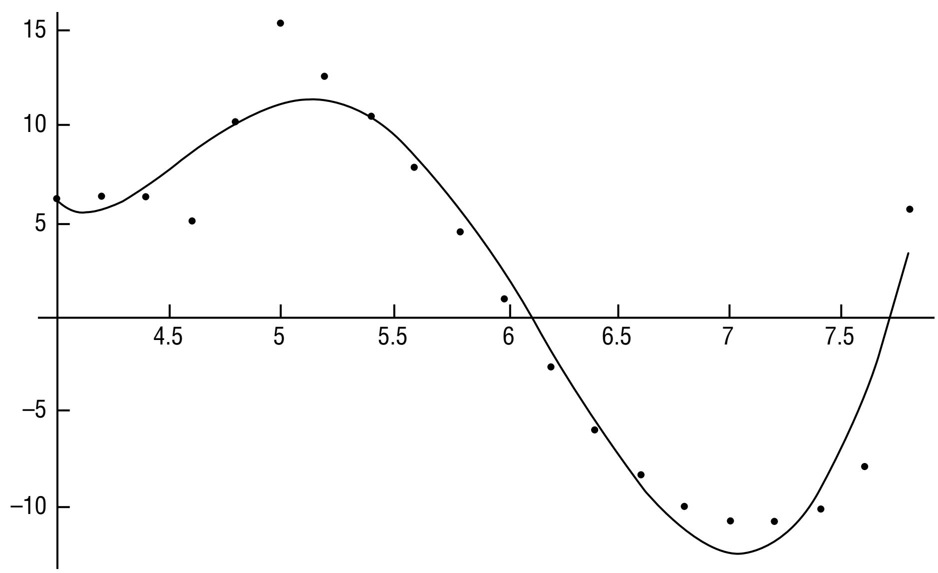
$4816.4 - 4219.77x + 1437.36x^2 - 236.9x^3 + 18.8426x^4 - 0.577482x^5$

Plot [%, {x, 4, 7.8}]



– Graphics –

Show [%, points]



– Graphics –

Figure 45. Display of NASA-DO-CE03-5.nb (screen 2).

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13. ABSTRACT *(Maximum 200 words)*

This report documents the development of analytical techniques required for interpreting and comparing space systems electromagnetic interference test data with commercial electromagnetic interference test data using NASA Specification SSP 30237A "Space Systems Electromagnetic Emission and Susceptibility Requirements for Electromagnetic Compatibility." The PSpice computer simulation results and the laboratory measurements for the test setups under study compare well. The study results, however, indicate that the transfer function required to translate test results of one setup to another is highly dependent on cables and their actual layout in the test setup. Since cables are equipment specific and are not specified in the test standards, developing a transfer function that would cover all cable types (random, twisted, or coaxial), sizes (gauge number and length), and layouts (distance from the ground plane) is not practical.

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